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An Array of Cold-Electron Bolometers with SIN Tunnel Junctions and JFET readout for Cosmology Instruments

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Abstract. A novel concept of the parallel/series array of Cold-Electron Bolometers (CEB) with Superconductor-Insulator-Normal (SIN) Tunnel Junctions has been proposed. The concept was developed specially for matching the CEB with JFET amplifier at conditions of high optical power load. The CEB is a planar antenna-coupled superconducting detector with high sensitivity. For combination of effective HF operation and low noise properties the current-biased CEBs are connected in series for DC and in parallel for HF signal. A signal is concentrated from an antenna to the absorber through the capacitance of the tunnel junctions and through additional capacitance for coupling of superconducting islands. Using array of CEBs the applications can be considerably extended to higher power load by distributing the power between N CEBs and decreasing the electron temperature. Due to increased responsivity the noise matching is so effective that photon NEP could be easily achieved at 300 mK with a room temperature JFET for wide range of optical power loads. The concept of the CEB array has been developed for the BOOMERanG balloon telescope and other Cosmology instruments.

1. Introduction

Recent Cosmology experiments have discovered that the Universe consists mainly of mysterious Dark Energy and Dark Matter [1]. Indeed, in 2006, a Nobel Prize was awarded for the experimental observation of anisotropies in the Cosmic Microwave Background (CMB) radiation, and the subsequent realization that the expansion of the Universe is controlled by unknown forces [2]. There are several cosmology instruments (BOOMERanG [3], OLIMPO, B-POL, CLOVER,…) that are being designed to measure anisotropies and the *B*-polarization in the CMB in order to detect gravity waves in the early moments of the Big Bang. Accurate measurement of the CMB should be done using a new generation of sensitive detectors.
An ultra-sensitive Cold-Electron Bolometer (CEB) [4,5] is one of the promising candidates for these experiments. The CEB concept is based on direct electron cooling of the absorber and provides high sensitivity and high saturation power. The CEB concept has been accepted as the main detector for 350 GHz channel of BOOMERanG [3]. The main requirement is to develop a CEB array for 92 channels with high polarization resolution. The NEP of the CEB with an JFET readout should be less than photon noise for optical power load of 10 pW.

A novel concept of the parallel/series array of Cold-Electron Bolometers (CEB) with Superconductor-Insulator-Normal (SIN) Tunnel Junctions has been proposed for effective matching with JFET amplifier under high power load. The main innovation in comparison with a single CEB [4-6] is effective distribution of power between N series CEBs and summarizing the increased response from

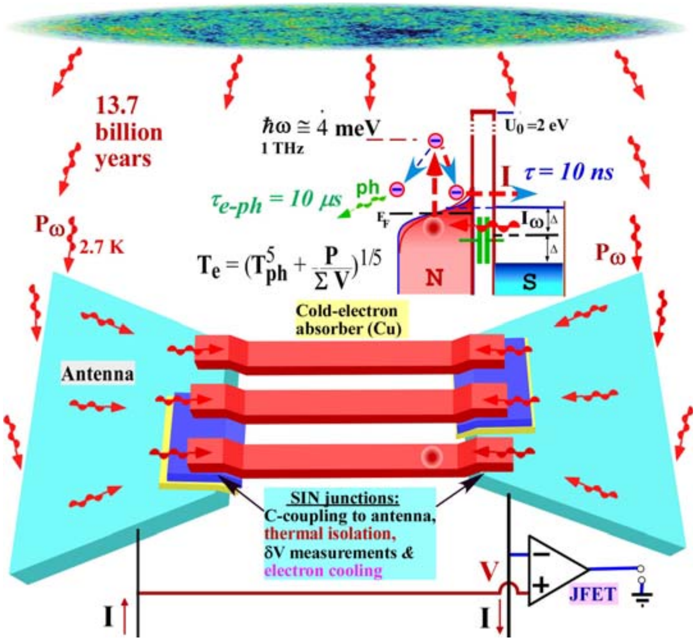

Figure 1. Schematic of a Cold-Electron Bolometer (CEB) with SIN Tunnel Junctions and JFET readout. The SIN junction is used for capacitive coupling to the antenna, thermal isolation, electron cooling and voltage response measurements.

the array. Effective distribution of power is achieved by parallel connection of CEBs for HF signal through capacitances. The response is increased because CEB is sensitive to the level of power and the power is N times decreased for the individual CEB with proportional decrease of absorber overheating. The high sensitivity of CEB for small power load has been predicted theoretically [4-6] and demonstrated experimentally [7]. A robust two layer technology can be used for fabrication of the CEBs with SIN tunnel junctions. In this paper we analyze the realization of the CEB array for 350 GHz channel of BOOMERanG and other Cosmology instruments.

2. Model

Here we analyze a system with the direct insertion of the CEB arrays into 4-probe antenna inside a circle waveguide (Fig. 2). In contrast to the previous concept of CEBs with coplanar lines [8], the HF region is strictly limited by the circle waveguide area. The optimal place for insertion is a point of connection between the probe and the waveguide with the maximum HF current. The problem of a DC bias of the CEB array from the side of a probe could be solved by introducing a narrow strip with very high inductive impedance between probes (Fig. 2a). A small isolation layer should be placed between strips in the centre of the waveguide. Two opposite CEB arrays are connected in series to get twice higher response for each polarization. The voltage response is measured by a JFET amplifier in a current-biased mode for each polarization. For typical JFET noise: 3 nV/Hz$^{1/2}$ & 5 fA/Hz$^{1/2}$, - the effective noise impedance is around 600 KOhm. The task of this concept is to match the total dynamic resistance of the array with the noise impedance of the amplifier and to divide power between CEBs in the array to increase the responsivity due to lower overheating and moderate electron cooling. The high noise impedance of a JFET amplifier is one of the reasons why a low-ohmic TES [9,10] could not be used this application.

The operation of a CEB array can be analyzed using the heat balance equation for a single CEB [11] taking into account power distribution between N bolometers:

$$\Sigma\lambda\left(T_e^5 - T_{ph}^5\right) + P_{SIN}(V, T_e, T_{ph}) + C_\lambda \frac{dT}{dt} = \frac{P_0 + \delta P(t)}{N} + 2\frac{V^2}{R_S} + I^2 R_A \qquad (1)$$

Here, $\Sigma\Lambda(T_e^5 - T_{ph}^5)$ is the heat flow from electron to the phonon subsystems in the normal metal, Σ is a material constant, Λ - a volume of the absorber, T_e and T_{ph} are, respectively, the electron and phonon temperatures of the absorber; P_{SIN} (V,T_e,T_{ph}) is cooling power of the SIN tunnel junctions; $C_v = \gamma T_e$ is the specific heat capacity of the normal metal; P_0 and $P(t)$ are the background and signal RF power, $2V^2/R_S$ is the heat load due to the subgap leakage resistance R_S of 2 SIN junctions, and I^2R_A is

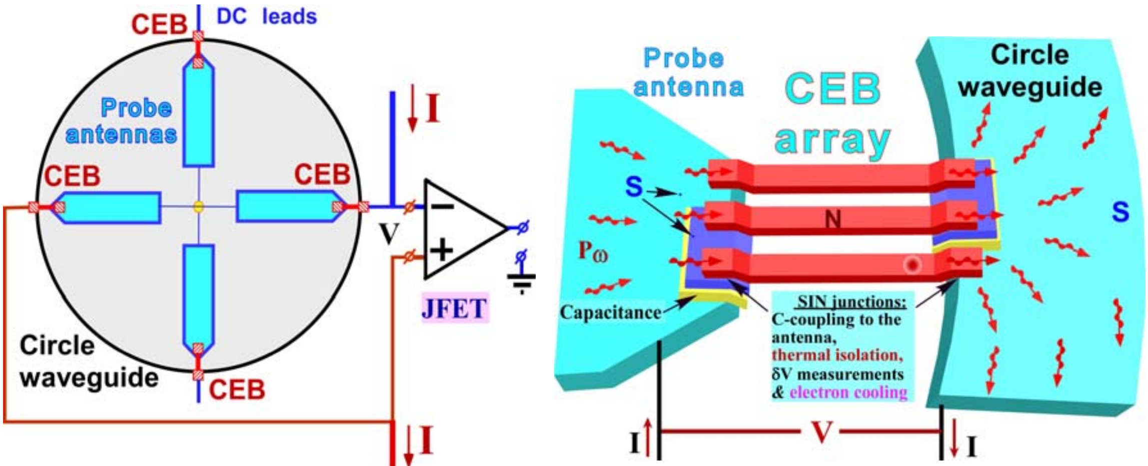

Figure 2. a) Direct connection of CEBs to a 4-probe antenna in a circle waveguide. CEBs in opposite probes are connected in series for each polarization. DC connection to JFET amplifier is shown for one polarization.

b) Each probe is really connected to an array of CEBs with series connection for DC and parallel for RF (schematically shown as a single CEB in figure 2a). For HF signal these CEBs are connected in parallel by the additional capacitances between superconducting islands and antenna.

the heat load due to the absorber resistance, R_A. We can separate Eq. (1) into the time independent term, $\Sigma\Lambda(T_{e0}^5 - T_{ph}^5) + P_{SIN0}(V, T_{e0}, T_{ph}) = P_0/N$, and the time dependent term,

$$(5\Sigma\Lambda\, T_e^4 + 2\left(\frac{\partial P_{SIN}}{\partial T} - \frac{\partial P_{SIN}}{\partial V}\frac{\partial I}{\partial T}/\frac{\partial I}{\partial V}\right) + i\omega C_\Lambda)\delta T = \delta P \cdot \qquad (2)$$

The first term,

$$G_{e-ph} = 5\Sigma\Lambda\, T_e^4 \,, \qquad (3)$$

is electron-phonon thermal conductance of the absorber. We should stress the strong dependence of $G_{e\text{-}ph}$ on the electron temperature. This is a key issue of the array realization of CEBs since this conductance must be decreased in order to improve noise properties. The second term

$$G_{SIN} = \frac{\partial P_{SIN}}{\partial T} - \frac{\partial P_{SIN}}{\partial V}\left(\frac{\partial I}{\partial T}/\frac{\partial I}{\partial V}\right) \qquad (4)$$

is the cooling thermal conductance of the SIN junction, G_{SIN}, which gives some electron cooling and help to avoid overheating of the absorber; the overheating would lead to decrease of the voltage responsivity $\delta V/\delta P$ because of strong dependence of this parameter on temperature.

A bolometer is characterized by its responsivity, noise equivalent power and the time constant. In the current-biased mode, the responsivity, S_V, is described by the voltage response to an incoming power

$$S_V = \frac{\delta V_\omega}{\delta P_\omega} = \frac{\partial V/\partial T}{G_{e-ph} + 2G_{SIN} + i\omega C_\Lambda} \qquad (5)$$

Noise properties are characterized by the noise equivalent power (*NEP*), which is the sum of three different contributions. For series array of CEBs, the NEP is defined as follows:

$$NEP_{tot}^2 = N * NEP_{e-ph}^2 + N * NEP_{SIN}^2 + NEP_{JFET}^2 \cdot \qquad (6)$$

Here

$$NEP_{e-ph}^2 = 10k_B\Sigma\Lambda(T_e^5 + T_{ph}^5) \qquad (7)$$

is the noise associated with electron-phonon interaction [11,12]; NEP^2_{SIN} is the noise of the SIN tunnel junctions, The SIN noise has three components: the shot noise $2eI/S^2_I$, the fluctuations of the heat flow through the tunnel junctions and the correlation between these two processes [11,12]:

$$NEP^2_{SIN} = \frac{\delta I^2_\omega}{(\frac{\partial I}{\partial V} S_V)^2} + 2\frac{< \delta P_\omega \delta I_\omega >}{\frac{\partial I}{\partial V} S_V} + \delta P^2_\omega . \tag{8}$$

This correlation is a form of the electrothermal feedback discussed earlier by Mather [13]. Due to this correlation the shot noise is increased at 30-50% in contrast to an SCEB with a superconducting absorber in voltage-biased mode where strong anti-correlation decreases the shot noise [14].
The last term is due to the voltage δV and current δI noise of the amplifier (JFET), which are expressed in nV/Hz$^{1/2}$ and pA/Hz$^{1/2}$:

$$NEP^2_{JFET} = \frac{\delta V^2 + (\delta I * (2Rd + Ra) * N)^2}{S_V^{\;2}} \tag{9}$$

The strong dependence on N decreasing this noise is included in the responsivity S_V, which is proportional to the N.
Along with the exact numerical results the approximate asymptotic formulas are also presented for understanding of basic dependences on number of bolometers. For moderate number of bolometers N, Te is larger than Tph and asymptotic expressions for Te and the responsivity can be derived in the first approximation:

$$T_e = (\frac{P_0}{N\Sigma\Lambda})^{1/5}, \ \frac{dV}{dT} = \frac{k}{e}\left[-\frac{(\Delta - eV)}{k}\left(\frac{N\Sigma\Lambda}{P_0}\right)^{1/5} + \frac{1}{2} \right], \ S_V = \frac{k}{e}\left[-\frac{(\Delta - eV)}{k}\left(\frac{N}{P_0}\right)\right] \tag{10}$$

The noise of JFET amplifier can be expressed as

$$NEP^2_{JFET} = \frac{\delta V^2}{S_V^{\;2}} = \frac{\delta V^2}{\left(\frac{k}{e}\right)\left[-\frac{(\Delta - eV)}{k}\left(\frac{N}{P_0}\right)\right]^2} . \tag{11}$$

Equations show a linear increase of responsivity *S* on number of bolometers *N* and linear suppression of NEP_{JFET} on *N* for given P_0.

3. Series array of CEBs in current-biased mode

The proposed mode of CEB operation is a current-biased array with voltage readout by a JFET amplifier. The analysis of a single current-biased CEB with JFET readout has shown that there is no chance to get photon noise level for high power load due to decreased responsivity and a JFET voltage noise [8]. Typical results for current-biased mode can be seen in figure 3 and figure 4 for N=1 (single bolometer). The main reason is degradation of voltage responsivity under high optical power load due to overheating of the absorber. Figure 3 shows increase of temperature, smearing IV-curve and decrease of responsivity for single CEB.

The only chance to achieve a photon noise level is to use a series DC connection of bolometers. However, series HF connections of bolometers would lead to real problems of junction size (for proper increase of capacitance) and overheating of islands. A special innovation has been proposed to combine these requirements: series connection for DC and parallel connection for RF. It could be realized by using additional capacitances for HF coupling as it is shown in figure 2b. In this case, the input power is divided between bolometers, the electron temperature is decreased and the CEBs return high responsivity while the output signal is collected from all bolometers.

The estimations were made for 350 GHz channel of BOOMERanG balloon telescope. For power load of P_0 = 5 pW per polarization, the photon noise could be estimated as

$$NEP_{phot} = \sqrt{2P_0 * hf} \;, \; NEP_{phot} = 4.3*10^{-17} W/Hz^{1/2} \;. \qquad (12)$$

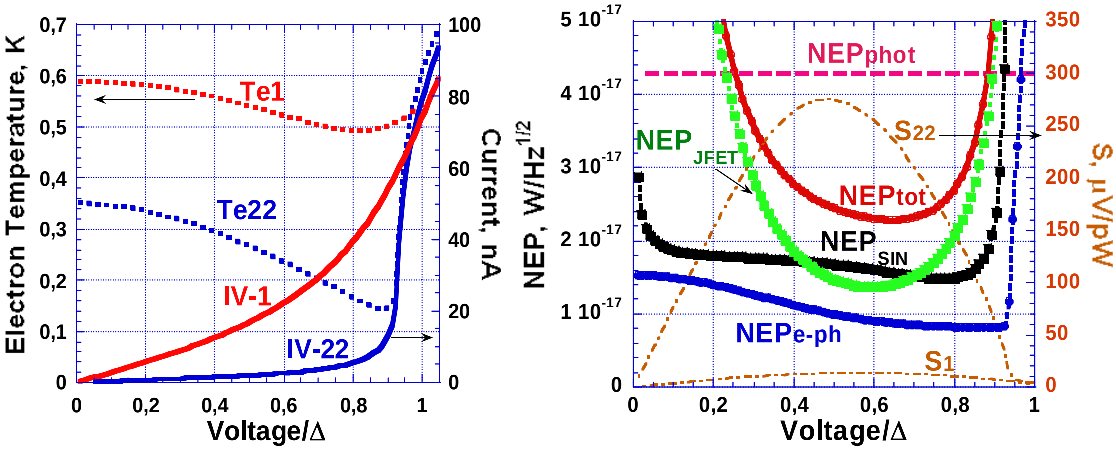

Figure 3. a) IV curves and electron temperature Te for the array of 22 CEBs and a single CEB; b) NEP components of the same CEB array for I_{JFET}=5 fA/Hz$^{1/2}$, V_{JFET}=3 nV/Hz$^{1/2}$, R=1 kOhm, Λ=0.01μm^3. The NEP_{tot} is less than NEP_{phot}. At the optimal point the background limited mode is realized (the total noise is limited by the noise of SIN junctions due to background power load). Responsivity is shown for a 22 CEB array, S22, and for a single CEB, S1, for comparison.

The total NEP of the detector+readout should be less than photon noise: $NEP_{tot} < NEP_{phot}$. We estimate an array of CEBs with different number of CEBs to achieve a low NEP with an JFET readout.

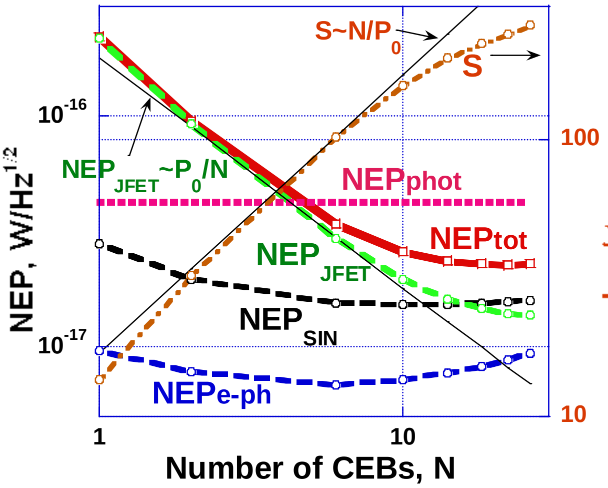

Figure 4. NEP components and photon NEP in dependence on the number of CEBs in a series array. The parameters of CEBs are the same as in figure 3. The responsivity S is shown for illustration of the effect of CEB number. Thin lines show asymptotics for S (10) and NEP_{JFET}(11).

The dependence of the noise components on number of bolometers is shown in figure 4. The total NEP achieves the level of photon noise for a number of CEBs larger than 6 (that means 3 for each probe). It is achieved mainly by suppression of contribution on JFET voltage noise due to increased responsivity (9). The figure demonstrates strong linear increase of the responsivity that becomes proportional to N when the number of bolometers is increased. This dependence is well supported by linear asymptotic (10). The noise of the JFET is proportionally decreased (11) which is the main goal of this realization. At the optimal point (N=22) the NEP_{JFET} is less than NEP_{SIN} that is manifestation of background limited mode of operation. NEP_{SIN} is increased proportionally to √N according to eq. 6 but decreased due to decrease of heat flow (and current) and increase of the responsivity S. These two effects approximately compensate each other and NEP_{SIN} is not sensitive to the number of the junctions. The most surprising is that NEPeph is not increased proportionally to the number of bolometers because the total volume of absorber is increased proportionally to the N (6,7). The reason is in compensation of this dependence is by some decrease in Te that is in the 5th power for Geph (3).

Optimal number of CEBs in series array. The optimal number is determined mainly by power load Po and the volume of absorber Λ. For not very small volume, the general rule of array design is the following: The number of bolometers, N, should be increased to split Po between bolometers up to the moment when $P_0/N= P_{ph}$, where $P_{ph} =T^5_{ph}\, \Sigma\Lambda$. The phonon power is determined by only one parameter, the volume of the absorber, Λ. There is no need to increase the number of bolometers to more than this figure because the optical power loading in each bolometer becomes less than the power from phonons. For very small absorber volume, the optimal number of bolometers is determined by interplay between amplifier noise and junction noise. The main rule here is to decrease the amplifier noise by increasing the number of CEBs to a level less than that of photon noise, using well-working approximation (11).

4. Conclusions

The analysis of a single current-biased CEB with JFET readout has shown that there is no chance to achieve photon noise level for high optical power load due to degradation of responsivity. However, the problem can be overcome using series array of CEBs for splitting a power load between the number of bolometers and increasing responsivity of the array. The special innovation has been proposed for HF matching using parallel connection of bolometers by special HF capacitance between superconducting islands and the antenna. Simulations show that this parallel/series array of bolometers could be used for any power load to achieve photon noise level with a JFET amplifier in current-biased mode. The volume of the absorber should be rather small for this purpose which can be easily achieved by nanolithography fabrication. In particular, for the 350 GHz channel of the BOOMERanG project with a power load of 5 pW per polarization the photon noise is equal to NEPphot=$4.3*10^{-17}$W/Hz$^{1/2}$. The CEB array noise at the level of NEP$_{tot}$=$2.3*10^{-17}$W/Hz$^{1/2}$ can be realized at 300 mK with a standard room-temperature JFET amplifier. The JFET amplifier is used in this case of a current-biased mode in the most straightforward way as a voltmeter.

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