An Antenna Coupled Cold-Electron Bolometer for High Performance Cosmology Instruments

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Abstract— **The newly emerging CMB polarization experiments (eg CLOVER, EBEX) employ detectors comprising transition-edge sensors (TES). The detectors will operate at temperatures of approximately 100 mK and will be read out by time division or frequency multiplexed SQUID amplifiers. Although detectors are expected to deliver impressive sensitivity, future space B-mode experiments (eg B-Pol) can benefit greatly from an increase in sensitivity, much higher saturation power, and flexibility in their realization on planar substrates.**

In this paper we describe a Cold-Electron Bolometer (CEB), which is a serious candidate for the next space cosmology missions. We analyze the suitability of various devices for the 70 GHz channel of the proposed B-Pol polarimeter. The detector may also be of interest to ground-based experiment as a result of the simplicity of its integration to planar circuit technology. The Capacitively Coupled CEB is a planar antenna-coupled superconducting detector with high sensitivity and high dynamic range. The CEB can meet noise requirements with both SQUID and JFET readouts. The SQUID readout can be used the same as for TES bolometers with typical SQUID sensitivity of 0.5 pA/Hz$^{1/2}$. An attractive realisation of the detector at millimetre wavelengths is to fabricate the CEB directly connected to the antenna on a planar substrate. The proper matching can be achieved by fabrication of an absorber strip of resistance equal to the wave impedance of the antenna.

Three variants of the CEB concept have been considered. The optimum realization of a CEB with SIN and SN tunnel junctions gives noise less than photon noise with SQUID readout. Estimations of the CEB noise with a JFET readout (at 300 K and 4.2 K) has shown an opportunity to realize background-limited performance for realistic power loading. Matching to a JFET is best obtained by using the SCEB (with weak superconducting absorber), and choosing a voltage bias in the flat region of the IV curve with very high dynamic resistance. This configuration can gives photon noise limited performance with JFET readout over a wide range of optical loading levels. Another possibility for matching to a JFET is a current-biased series array of CEBs with normal metal absorbers, connected in parallel for HF signal.

The antenna-coupled CEB bolometer is easy to couple to a wide range of planar antennae systems, either on bulk or membrane substrates. Applicability of the CEB to B-Pol and similar space missions looks very promising for all of the frequency bands and with both JFET and SQUID readout schemes.

Index Terms— Cold-Electron Bolometer, SIN tunnel junction, Josephson junction, Andreev contact, SQUID readout

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I. 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 (B-Pol [3], BOOMERanG, [4], CLOVER [5], EBEX, BICEP, QUIET,) that are being designed to measure the polarization state of the Cosmic Microwave Background (CMB), in particular the *B*-mode polarization, which is generated by primordial gravitational waves.

It is well known, however, that ground-based experiments are severely limited by atmospheric noise even at best sites. Consequently, space-borne CMB polarization instruments are now being planned both in the USA and Europe. A European consortium has already been assembled to design the next ESA CMB cosmology instrument. An expression of interest has recently submitted to ESA, as part of the Cosmic Vision Call, to support a medium-scale space mission called B-Pol [3] .

A new generation of detectors is needed for these advanced telescopes, and these detectors must achieve sensitivities better than ~10^{-18} W/Hz$^{1/2}$. One of these technologies is the Capacitively Coupled Cold-Electron Bolometer (CEB) [6]-[8]. The CEB can be used with both JFET [9] and with SQUID readout [6],[8]. The JFET readout has been used for the latest astronomy missions, and the SQUID readout and multiplexing has been developed for TES (Transition-Edge Sensor) bolometers [10,11]. Overall, the goal is to achieve, with a CEB read out by a JFET or SQUID, a noise-equivalent power that is less than the photon noise of the CMB radiation.

The CEB is a planar antenna-coupled superconducting detector with high sensitivity and high dynamic range. It operates through electron cooling by SIN tunnel junctions, and with strong electrothermal feedback [6]. To achieve noise matching to the estimated in-flight optical power load, different concepts of the CEB, with SQUID and JFET readouts, must be analyzed. In this paper, we analyze an optimal configuration having one SIN junction and an Andreev SN contact, and SQUID readout. We also analyse a SCEB with a superconducting absorber, and a parallel/series array of CEBs with JFET readout for the 70 GHz channel of B-Pol.

To increase the CEB efficiency in voltage-biased mode, for current readout, an optimal configuration with a capacitively coupled SIN junction and an Andreev SN contact [12] has been selected (Fig. 1). This concept has been invented to improve the noise properties by increasing the responsivity of the CEB with SQUID readout. An important feature of the design is that the volume of the normal metal is partly squeezed due to the proximity effect of the superconducting electrode of the Andreev contact. This squeezing further increases the efficiency of the electron cooling without degrading the HF coupling.

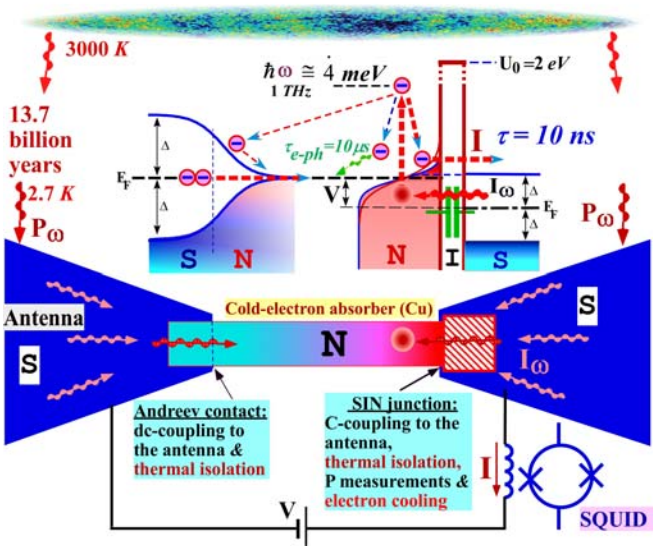


Fig 1. Schematic of the optimal Cold-Electron Bolometer (CEB) with capacitive coupling to the antenna and a SQUID readout. The CEB comprises a planar superconducting antenna and an absorber coupled through the capacitance of an SIN tunnel junction, and an SN Andreev contact. The SIN tunnel junction is used also for electron cooling, and for reading out the signal with a SQUID.

Detection using this device is obtained by allowing the incoming signal to pass from the antenna to the absorber through the capacitance of a tunnel junction and an Andreev contact. RF matching is realized by the resistance of a normal absorber, which is independent of the tunnel junction parameters.

The concept is based on *direct electron cooling* of the absorber, which provides strong *negative electrothermal feedback* for the signal. This feedback is analogous to the TES [10,11], but artificial dc heating is replaced by *direct electron cooling* to a minimum temperature. This innovation can lead to a major breakthrough in realizing supersensitive detectors. The noise properties of this device are improved considerably by decreasing the electron temperature. The loop gain of the electrothermal feedback can exceed 1000. The response time is reduced, by electrothermal feedback, to 10 ns compared to the intrinsic e-ph time constant of 10 µs.

The CEB in voltage-biased mode allows a substantial increase in the dynamic range, by removing incoming power from the absorber. The current flowing through the tunnel junction is readout by a SQUID, which intrinsically has a high dynamic range. The CEB with one SIN junction and one Andreev contact has almost twice the responsivity of the traditional CEB with two SIN junctions in series.

II. MODEL

In what follows we shall use the basic concept of the CEB with strong electrothermal feedback due to electron cooling. This structure has been analyzed in detail in Ref. [6],[13]. The operation of CEB can be described using the heat balance equation:

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

Here, $\Sigma\Lambda(T_e^5-T_{ph}^5)$ is the heat flow from the electron to the phonon subsystems in the absorber, Σ is a material constant, Λ is the volume of the absorber, T_e and T_{ph} are, respectively, the electron and phonon temperatures of the absorber; $P_{cool}(V,T_e,T_{ph})$ the cooling power of the SIN tunnel junction; $C_\Lambda = \Lambda\gamma T_e$ is the specific heat capacity of the absorber; Rj the subgap resistance of the tunnel junction; Rabs the resistance of the absorber; *P(t)* the incoming rf power. We can separate Eq. (1) into the time independent term, $\Sigma\Lambda(T_{e0}^5-T_{ph}^5)+P_{cool\,0}(V,T_{e0},T_{ph})=P_0$, and the 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 first term, $G_{cool}=\partial P_{cool}/\partial T$, is the cooling thermal conductance of the SIN junction that gives the negative electrothermal feedback (ETF); when it is large, it reduces the temperature response δT because cooling power, P_{cool}, compensates the change of signal power in the bolometer. The second term, $G_{e-ph}=5\Sigma\Lambda T_e^4$, is 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

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

In analogy with TES [11], the effective thermal conductance of the CEB is increased by the effect of electron cooling (negative ETF).

Here we assume that the SIN tunnel junction is voltage-biased, and the current is measured by a SQUID [6],[12]. 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,

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

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

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

is an effective time constant, $\tau_0=C_\Lambda/G_{e-ph}$ ($\cong 10\mu s$ at 100 mK).

The strength of the electrothermal feedback is estimated as:

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

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

$$NEP_{total}^2 = NEP_{e-ph}^2 + NEP_{SIN}^2 + \delta I^2 / S_I^2 \quad (7)$$

$$NEP_{e-ph}^2 = 10 k_B \Sigma \Lambda (T_e^6 + T_{ph}^6) \quad (8)$$

is the noise associated with electron-phonon interaction; NEP^2_{SIN} is the noise of the SIN tunnel junctions, and the last term $\delta I^2/S^2_I$ is the noise of an amplifier (SQUID): δI, is expressed in pA/Hz$^{1/2}$.

The noise of the SIN tunnel junctions, NEP^2_{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 [13],[14].

$$NEP_{SIN}^2 = \delta P_\omega^2 - 2\frac{\delta P_\omega \delta I_\omega}{S_I} + \frac{\delta I_\omega^2}{S_I^2} . \quad (9)$$

This anticorrelation is a form of the electrothermal feedback discussed earlier by Mather [15].

III. THE CEB WITH SIN TUNNEL JUNCTION AND SN CONTACT AND SQUID READOUT

The analysis of the Cold-Electron Bolometer (CEB) shows that the optimal configuration of the bolometer in voltage-biased mode is a CEB with a single SIN Junction and an Andreev SN contact [12]. Any use of a double junction in

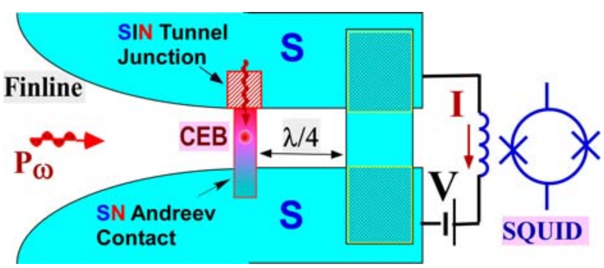


Fig. 2. A Cold-Electron Bolometer (CEB) coupled to a finline antenna with SQUID readout.

voltage-biased mode [6,8] would lead to the splitting power between two junctions and a degradation of responsivity. The optimal readout is a SQUID, and voltage bias.

We have analyzed the concept of an optimal cold-electron bolometer for 70 GHz channel of B-Pol polarometer in the presence of the typical power load (P_0 = 0.2 pW

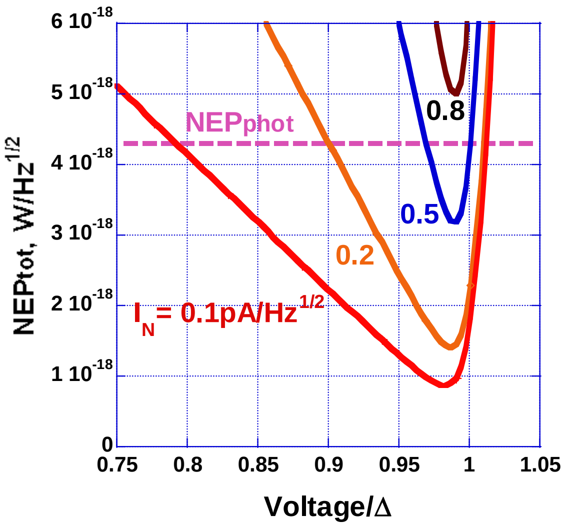


Fig. 3 Total NEP of the CEB with SIN tunnel junction for the 70 GHz channel, with a SQUID noise current from 0.1 pA/Hz$^{1/2}$ and 0.8 pA/Hz$^{1/2}$. R=0.2 kOhm, S=2μm^2, Vol=0.03um^3, power load P_0 = 0.2 pW, T=100 mK. The NEPphot= 4.3*10^{-18} W/Hz$^{1/2}$ is shown by dashed line.

per polarization component) [3].

Photon noise: $$NEP_{phot} = \sqrt{2P_0 * hf} \quad (10)$$

For the 70GHz channel, NEPphot= 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$^{1/2}$. The level of NEPphot has been achieved for SQUID noise lower than 0.5 pA/Hz$^{1/2}$

IV. THE SCEB WITH SIS' AND JOSEPHSON JUNCTIONS IN *VOLTAGE-BIASED MODE* WITH JFET READOUT

We shall now discuss a second scheme, which matches the moderate dynamic resistance of the CEB (~1÷10 kOhm) to the high noise equivalent resistance of a JFET (~1 MΩ). To achieve noise matching to a JFET, a Cold Electron Bolometer with a weak Superconducting absorber (SCEB) has been proposed [9]. In voltage-biased mode, with a voltage higher than the difference gap, an SIS′ junction has a considerably increased dynamic resistance that is used to suppress voltage noise of JFET. However, the use of two series tunnel junctions is not optimal for voltage-biased mode [12]. A CEB with an SIS′ junction and a SS′ Andreev-type contact (similar to optimal bolometer with SIN and SN contacts [12]) could solve this problem, but would bring complicated 3-layer technology.

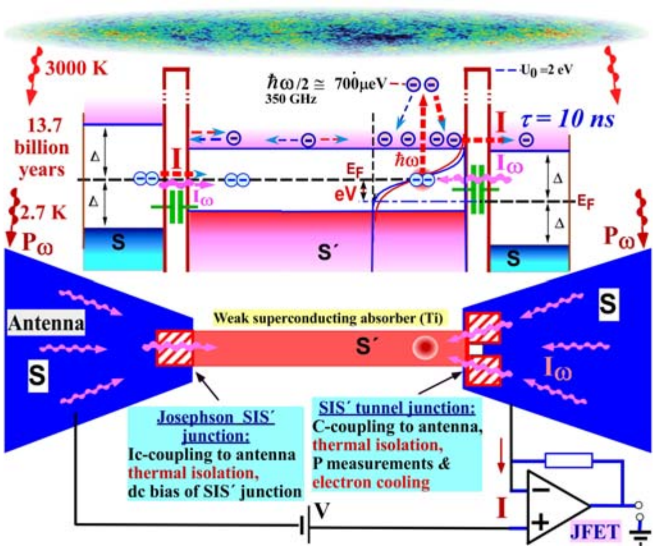


Fig 4. Schematic of a Superconducting Cold-Electron Bolometer (SCEB) with SIS´ and Josephson Tunnel Junctions and a JFET readout [16]. The SIS´ junction is used for capacitive coupling to the antenna, thermal isolation, electron cooling and dc readout by a JFET. The Josephson junction is used for dc and RF contacts, and for thermal isolation. SIS´ junction is made in a loop geometry for easy suppression of a critical current by a weak magnetic field.

A novel concept of a Superconducting Cold-Electron Bolometer (SCEB) with SIS´ and Josephson tunnel junctions (Fig. 4) has been proposed recently [16]. The main innovation in comparison with previous concepts of the CEB in voltage-biased mode is the effective use of a Josephson junction for dc and RF contacts, and for thermal isolation. The SIS´ junction (for RF coupling, thermal isolation, electron cooling and dc readout) is proposed in a loop geometry for suppressing the critical current by a weak magnetic field. A remarkable feature of this concept is that the critical current of the Josephson junction is not completely suppressed by a weak magnetic field. As a result, a robust two layer technology can be used in fabrication of both the SIS´ and Josephson tunnel junctions simultaneously. In this paper we analyzed a realization of the SCEB for the 70 GHz channel of B-POL.

For RF coupling we have chosen a 4-probe antenna in circle waveguide with direct connection of SCEBs to the antenna (Fig. 5a) [16]. In contrast to a previous concept of the SCEB with coplanar lines [9], the RF region is strictly limited by the circular waveguide area. The optimal point for the CEB is shown in the diagram, where the RF current is greatest. The problem of DC bias of an SIS´ junction could be solved by introducing one more Josephson junction at the right end of the absorber (Fig. 5b). Two opposite SCEBs are connected in parallel, for each polarization, by dc leads, and measured by JFET in voltage-biased mode. The optimal bias point of SIS´ junction is between the difference and sum gaps where the I-V curve has increased dynamic resistance (Fig. 6). For the JFET noise, 3 nV/Hz$^{1/2}$ & 5 fA/Hz$^{1/2}$, the effective noise impedance is around 600 KOhm. The suppression of the JFET voltage noise is important for this realization. Current noise in a JFET are rather low, at the level of 5fA/Hz$^{1/2}$. The high noise impedance of a JFET amplifier is one of the reasons why a low-ohmic TESs [9,10] cannot be matched with JFETs.

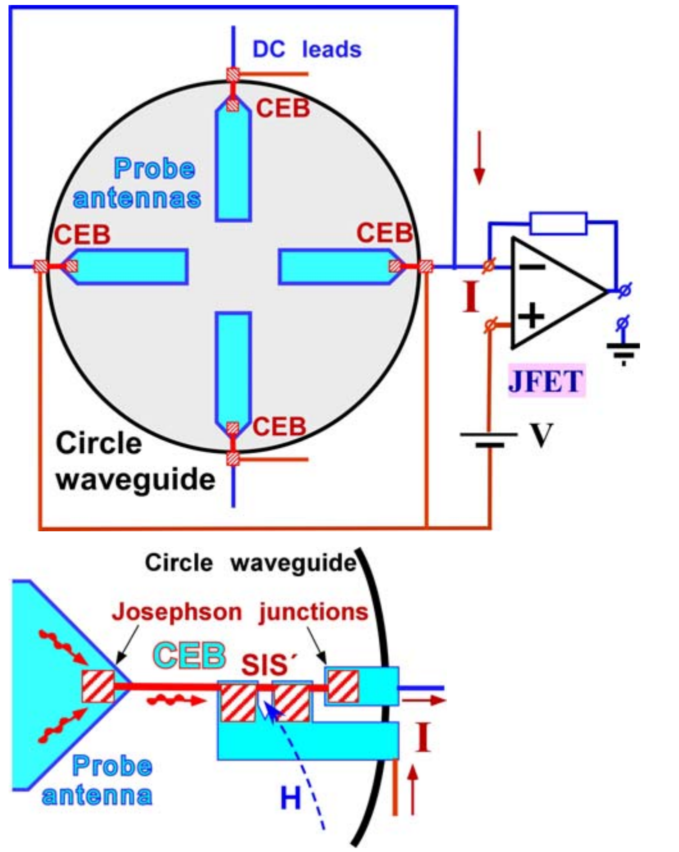


Fig 5. a) Direct connection of CEBs to a 4-probe antenna in a circular waveguide [16]. CEBs in opposite probes are connected in parallel for each polarization. b) A detail of the CEB connected to a probe antenna with an additional Josephson junction for dc bias supply.

For the analysis we use a previous concept of the CEB with strong electrothermal feedback, due to electron cooling [6,8,13], and with a superconducting absorber [9]. For an optical power load of P_0 = 0.2 pW per polarization for the 70 GHz channel of B-Pol, the photon noise is NEPphot = 4.3*10^{-18} [3].

Figure 3 shows simulations of the different contributions to

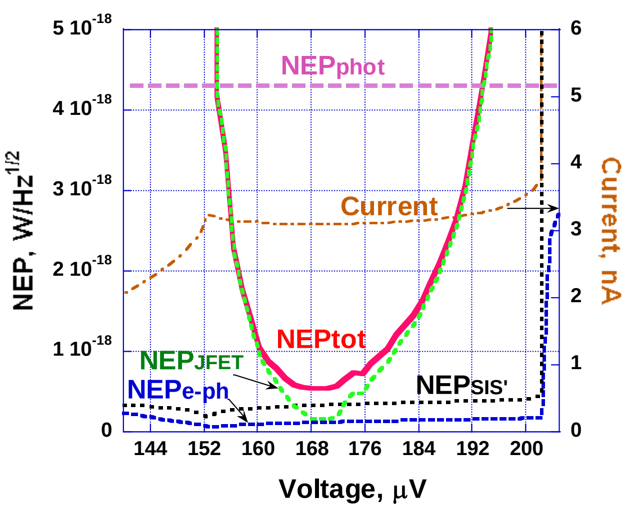


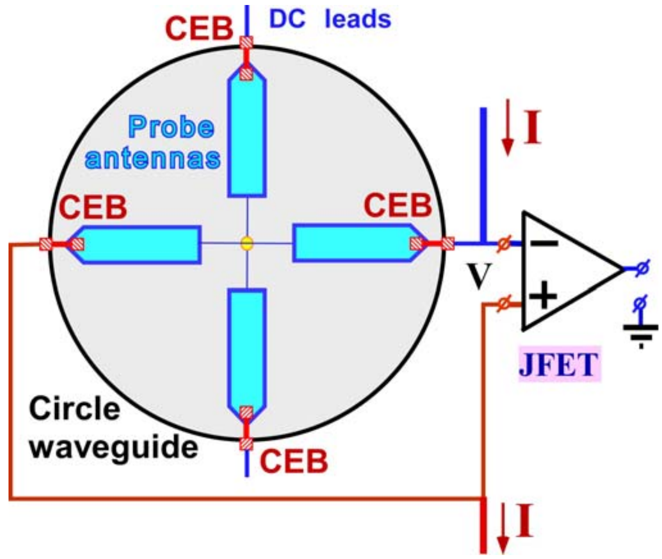
Fig. 6. NEP components of the SCEB with JFET readout for I_{JFET}=5 fA/Hz$^{1/2}$, V_{JFET}=3 nV/Hz$^{1/2}$, R=1 kOhm, Λ=0.02μm^3, power load P_0 = 0.2 pW per polarization. IV curve is shown for estimation of a high dynamic resistance of the junctions. The NEPphot= 4.3*10^{-18} W/Hz$^{1/2}$ is shown by dashed line.

the total NEP of the bolometer. We see that for a range of bias voltage from 155 μV to 195 μV, the total NEP of the SCEB is well below the photon noise: $NEP_{tot} < NEP_{phot}$. The range of voltages from 155 μV to 170 μV is not recommended for use because, due to negative slope the IVcurve, the operating point would be unstable. In addition, the NEP_{tot} of the SCEB is dominated at the optimum point by the shot/heat noise of the detector, $NEP_{SIS'}$, (9) corresponding to the background limited mode of operation. Equation (9) includes the effect of the noise reduction of SIS′ tunnel junction due to the anticorrelation term. The final noise, $NEP_{SIS'}$, is less than noise components. The effect is stronger than for SIN junction noise [12] due to the well-defined level of the quasiparticle energy just near the superconducting gap.

V. THE CEB ARRAY WITH SIN TUNNEL JUNCTIONS IN *CURRENT-BIASED MODE* WITH JFET READOUT

An alternate mode of CEB operation is a novel concept employing a parallel/series array of CEBs with SIN Tunnel Junctions, for effective matching to a JFET amplifier [17] (Fig. 7). Previous analysis of a single current-biased CEB with JFET readout showed that the JFET input voltage noise limits the sensitivity [9]. The main reason is the degradation of voltage responsivity under high optical power load. The main innovation of the CEB array is the distribution of power between N series CEBs, and summarizing the increased response from the array. Effective distribution of power is achieved by a parallel connection of CEBs, which couple to the RF signal through additional capacitances (Fig. 7b). The response is increased because the CEB is sensitive to the level of power, and the power is decreased N times for the individual CEBs, with a proportional decrease of absorber overheating.

The high sensitivity of the CEB for small power loads has been analyzed theoretically [6,8,13], and demonstrated experimentally [18]. In this paper we analyze a realization of the CEB array for the 70 GHz channel of B-Pol. For RF coupling we analyze a system with the direct insertion of the CEB arrays into a 4-probe antenna inside a circular waveguide (Fig. 7). The system is similar to the previous 4-probe system with SCEBs (Fig. 5), with the replacement of the SCEBs by the CEB arrays, and with the replacement of the parallel connection to a series connection of opposite CEBs. The problem of DC biasing the CEB arrays can be solved by interconnecting opposite probes by a narrow strip with very high inductive impedance (Fig. 7a). 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 two-times higher response for each polarization. The voltage response is measured by a JFET amplifier in a current-biased mode. The main purpose of this concept is to match the total dynamic resistance of the array to the noise impedance of a JFET (~0.6 MΩ). The power should be divided between the CEBs in the array to increase the responsivity due to lower overheating and moderate electron cooling.



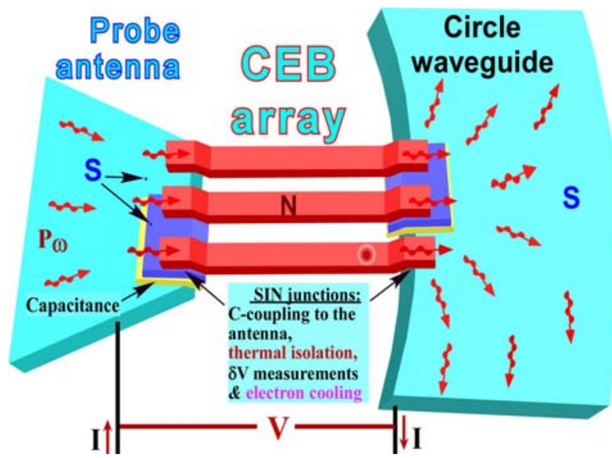


Fig 7 a) Direct connection of CEBs to a 4-probe antenna in circlar waveguide [17]. CEBs in opposite probes are connected in series by a narrow strip for each polarization. b) Each probe is really connected to an array of CEBs with series connection for DC and parallel for RF (schematically shown as a single CEB in the top figure). For RF the CEBs are connected in parallel by additional capacitances between superconducting islands and antenna.

The operation of a CEB array can be analyzed using the heat balance equation for a single CEB [13] taking into account power distribution between the N bolometers. The responsivity S_V is described by the voltage response to an incoming power

$$S_V = \frac{\delta V_\omega}{\delta P_\omega} = \frac{\partial V / \partial T}{G_{e-ph} + 2G_{SIN} + i\omega C_\Lambda} \tag{10}$$

The second term

$$G_{SIN} = \frac{\partial P_{SIN}}{\partial T} - \frac{\partial P_{SIN}}{\partial V}\left(\frac{\partial I}{\partial T} / \frac{\partial I}{\partial V}\right) \tag{11}$$

is the cooling thermal conductance of the SIN junction, G_{SIN}, which gives some electron cooling and help to avoid overheating of the absorber.

Noise properties are characterized by the noise equivalent power (*NEP*), which is the sum of three contributions:

$$NEP_{tot}^2 = N * NEP_{e-ph}^2 + N * NEP_{SIN}^2 + NEP_{JFET}^2. \tag{12}$$

Here $NEP_{e\text{-}ph}$ is the same electron-phonon noise as in Eq. 8. NEP_{SIN} is the noise of the SIN tunnel junctions. The SIN noise has three components: the shot noise $2eI/S2I$, the fluctuations of the heat flow through the tunnel junctions and the correlation between these two processes [13-15]:

$$NEP_{SIN}^{2} = \frac{\delta I_{\omega}^{2}}{\left(\frac{\partial I}{\partial V} S_V\right)^2} + 2\frac{<\delta P_{\omega}\delta I_{\omega}>}{\frac{\partial I}{\partial V} S_V} + \delta P_{\omega}^{2} \quad . \qquad (13)$$

Due to this *correlation* the shot noise is increased at 30-50% in contrast to the CEB in voltage-biased mode (9) where strong *anti-correlation* decreases the shot noise.

The last term is due to the voltage δV and current δI noise of a JFET, which are expressed in nV/Hz$^{1/2}$ and pA/Hz$^{1/2}$:

$$NEP_{JFET}^{2} = (\delta V^2 + (\delta I*(2Rd+Ra)*N)^2)\Big/ S_V^{\,2} \qquad (14)$$

The strong dependence on N, decreasing this noise is included in the responsivity S_V, which is proportional to N.

The estimations were made for the 70 GHz channel of BPol.

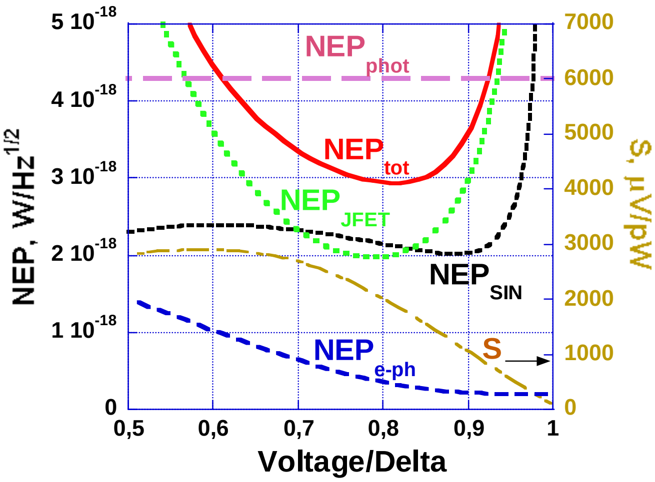


Fig. 8. NEP components of the array of 10 CEBs with JFET readout at 70 GHz with power load of 0.2 pW for I_{JFET}=5 fA/Hz$^{1/2}$, V_{JFET}=3 nV/Hz$^{1/2}$, R=4 kOhm, Λ=0.03μm^3, T=100 mK.

We have simulated arrays of CEBs with different numbers of CEBs, from 1 to 14, to achieve a low NEP with JFET readout. Fig. 8 shows typical results of an NEP simulation for the optimal array of 10 CEBs. We see that for a range of normalized voltage from 0.62 to 0.93, the total NEP of the CEB array is less than the photon noise. At the optimum point, background limited performance is realized (the total noise is determined by the noise of SIN junctions, NEP_{SIN}, (13) due to background power load).

The dependence of the noise components on the number of bolometers is shown in Figure 9. The total NEP decreases to a level less than photon noise for a number of CEBs larger than 6 (3 for each probe). It is achieved mainly through the suppression of the JFET noise component due to the increased responsivity (10). Figure 9 demonstrates a strong linear increase of the responsivity proportional to N when the number of bolometers is increased. The noise of the JFET (14) is proportionally decreased, which is the main goal of this realization. Around the optimum point (N=10) the NEP_{JFET} is less than NEP_{SIN} , which is a manifestation of background-limited operation. The NEP_{SIN} increases proportionally to √N (according to eq. 6), but decreases due to a decrease of the heat flow (and current) and an increase of the responsivity S. These two effects approximately compensate each other, and NEP_{SIN} is not very sensitive to the number of the bolometers. The most surprising result is that the NEPeph (8) is not increased proportionally to the number of bolometers when the total volume of absorber is increased proportionally to N. The reason is due to a compensation of this dependence by some decrease in Te that is in the 6th power for NEPeph (8).

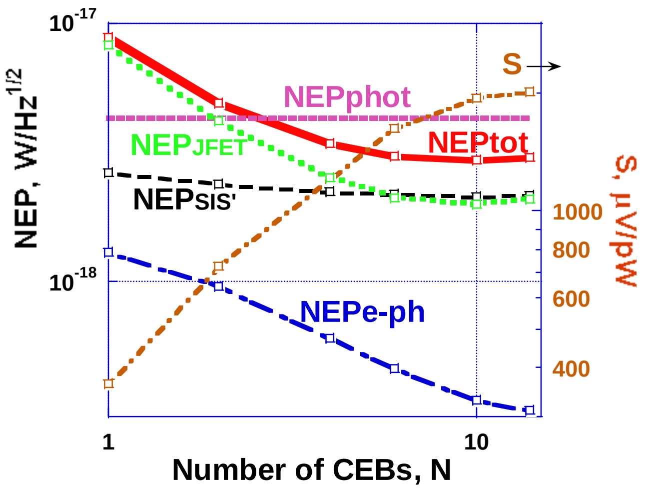


Fig. 9. NEP components and photon NEP in dependence on the number of CEBs in a series array. The parameters of CEBs are the same as in Fig. 8. The responsivity S is shown for illustration of the effect of the CEB number.

Optimal number of CEBs in series array. The optimal number is determined mainly by the power load Po and the volume of absorber Λ. 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 point 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 more than this figure because the optical power loading in each bolometer becomes less than the power from phonons. Responsivity is saturated after this level.

VI. Conclusion

We have analyzed several variations of the concept of a Cold-Electron Bolometer (CEB) with an SIN (Superconductor-Insulator-Normal Metal) or SIS´ (Superconductor-Insulator-Weak Superconductor) tunnel junctions for realization of the requirements of future space projects. These concepts give unique opportunities to achieve NEPs less than photon noise for any optical power loading with standard JFET or SQUID readouts. Three variants of the CEB concept have been considered for the 70 GHz channel of B-Pol. The first optimal solution is a CEB with SIN and SN tunnel junctions which gives noise less than photon noise with SQUID readout.

For matching the device to a JFET readout we have analyzed the SCEB (with weak superconducting absorber) choosing a voltage bias in the flat region of the IV curve with very high dynamic resistance. This configuration can give background

limited performance with total noise considerably less than photon noise. Another concept for matching with JFET readout is a current-biased series array of CEBs with normal metal absorbers, connected in parallel for the RF signal. This concept has also demonstrated total noise less than the background photon noise.
Several variants of RF coupling of CEBs to finline and a 4-probe antenna have been proposed. We have shown that the CEB is an ideal antenna-coupled bolometer that can be easily integrated to any antenna system on a bulk or membrane substrate. Applicability of the CEB to BPol and similar space missions looks very promising for the whole range of frequency bands, and with both JFET and SQUID readout.

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