Distributed Antenna Coupled Cold-Electron Bolometers for Focal Plane Antenna

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Abstract— **Novel concepts of the parallel and series array of Cold-Electron Bolometers (CEB) with Superconductor-Insulator-Normal (SIN) Tunnel Junctions have been proposed for distributed focal plane antenna. The arrays are developed for a pixel design based on arrays of CEBs coupled to a distributed slot antenna or dipole antenna.**

Two variants of the CEB arrays have been considered for both types of antenna on bulk substrate. The parallel connection of CEBs with SIN tunnel junctions in voltage-biased mode is optimal for a slot antenna. Some improvement of properties can be achieved by using optimal configuration of CEB with SIN junction and Andreev contact. Remarkable progress in performance is expected from implementation of a new technology for fabrication of the CEB and SQUID on the same chip in one vacuum circle. Estimations of the CEB noise with SQUID readout have shown an opportunity to realize background-limited performance for typical power load of 5pW proposed for BOOMERanG.

The series connection of CEBs with SIN tunnel junctions in current-biased mode is optimal for dipole antennas. Estimations of the CEB noise with JFET readout have shown an opportunity to realize NEP less than photon noise for typical power load.

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

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 , 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 design of antennas and a new generation of detectors are needed for these advanced telescopes, and these detectors must achieve sensitivities better than $\sim 10^{-18}$ W/Hz$^{1/2}$. One of these technologies is the Capacitively Coupled Cold-Electron Bolometer (CEB) [5]-[9]. It operates through direct electron cooling of an absorber by SIN tunnel junctions, and with strong electrothermal feedback [5]. The strong electrothermal feedback is similar to TES (Transition-Edge Sensor) [11,12] with replacement of additional dc heating (TES) by effective electron cooling (CEB) with proper improvement of noise properties and dynamic range. The CEB can be used with both SQUID readout [5,7,9] and JFET [8,10]. The JFET readout has been used for the latest astronomy missions, and the SQUID readout and multiplexing is in process of development for TES. 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 that can be easy matched with any planar antenna. Very attractive direction developed in Caltech is distributed focal plane antennas [13,14]. These antennas could help to avoid horns or Si lenses for matching with bolometers. This type of antenna is in ESA plan for developing and testing for B-Pol [3]. Our current interest is to test this antenna for balloon project BOOMERANG [4].

To achieve RF matching to a distributed focal plane antenna, different concepts of the CEB, with SQUID and JFET readouts, must be analyzed. In this paper, we analyze parallel and series arrays of CEBs for matching with slot and dipole antennas. The system is purposed for BOOMERANG balloon telescope and later can be used for B-Pol and other cosmology instruments.

An optimal configuration of CEB with a capacitively coupled SIN junction and an Andreev SN contact [7] has been selected (Fig. 1) for parallel combination of CEBs to match with a slot antenna. This concept has been invented to improve the noise properties by increasing the responsivity of the CEB in voltage-biased mode with SQUID readout in comparison with "classical" series connections of SIN junctions [5]. 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 from SN Andreev contact. This squeezing further increases the efficiency of the electron cooling without degrading the HF coupling.

Remarkable progress in performance is expected from implementation of a new technology for fabrication of the CEB and SQUID on the same chip in one vacuum circle [15]. Simultanious fabrication of CEB and SQUID on-chip would create more reliable structures and avoid interferences due to wire interconnections of the systems.

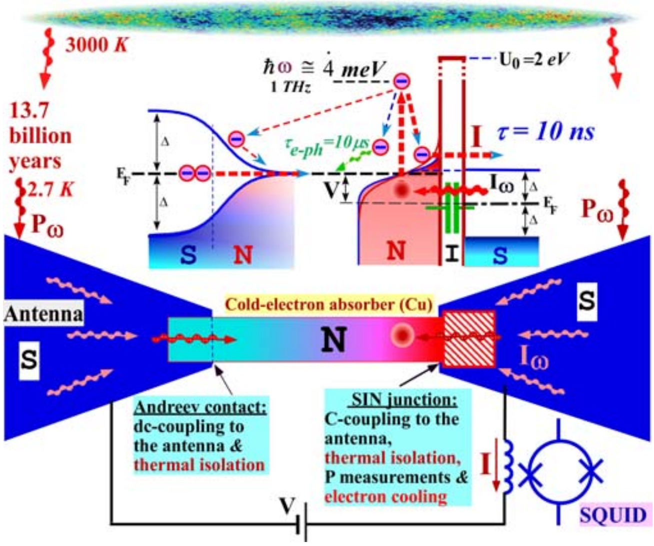

Fig 1. Schematic of the **optimal Cold-Electron Bolometer (CEB) with capacitive coupling to the antenna** and a SQUID readout. The CEB comprises a planar superconducting antenna and an absorber coupled through the capacitance of an SIN tunnel junction, and an SN Andreev contact. The SIN tunnel junction 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 [11,12], 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. [5],[16]. The operation of CEB can be described using the heat balance equation:

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

(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,

$$\Sigma\Lambda(\boldsymbol{T}_{\boldsymbol{e}0}^5-\boldsymbol{T}_{\boldsymbol{ph}}^5)+\boldsymbol{P}_{\boldsymbol{cool}\,0}(\boldsymbol{V},\boldsymbol{T}_{\boldsymbol{e}0},\boldsymbol{T}_{\boldsymbol{ph}})=\boldsymbol{P}_0,$$ and the time dependent term,

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

(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, $\boldsymbol{G}_{\boldsymbol{e-ph}}=5\Sigma\Lambda\boldsymbol{T}_{\boldsymbol{e}}^4$, 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

$$\boldsymbol{G}_{\boldsymbol{eff}}=\boldsymbol{G}_{\boldsymbol{cool}}+\boldsymbol{G}_{\boldsymbol{e-ph}}+\boldsymbol{i\omega C}_\Lambda$$

(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 [5,7,9]. 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 $L = G_{cool}\big/G_{e-ph} >> 1$ is ETF gain and

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

is an effective time constant, $\tau_0 = C_\Lambda\big/G_{e-ph}$ ($\cong 10\mu s$ 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:

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

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

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 [16],[17].

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

This anticorrelation is a form of the electrothermal feedback discussed earlier by Mather [18].

III. PARALLEL ARRAY OF CEB WITH SIN TUNNEL JUNCTIONS AND SQUID READOUT

The analysis of an array of the Cold-Electron Bolometers (CEB) for the slot antenna (Fig. 2) shows that the optimal configuration is a parallel array of the CEBs with SIN tunnel junctions in voltage-biased mode [5]. All CEBs are connected in parallel for dc bias. This slot antenna will be sensitive only to one horizontal component of RF signal.

The further improvement of performance could be achieved by using the optimal CEB in voltage-biased mode with a single SIN Junction and an Andreev SN contact [7]. Any use of a double junction in voltage-biased mode [5,7] would lead to the splitting power between two junctions and some degradation of responsivity. The Al-Al SQUID and CEB with SIN tunnel junctions could be fabricated on the same chip in the same vacuum circle [15]. Simultaneous fabrication of CEB and SQUID on-chip would create more reliable structures and avoid interferences due to wire interconnections of the systems. Total structure with CEB, SQUID with magnetic coil, antenna, and protective resistors would take three e-beam exposures and one photolithography for contact pads.

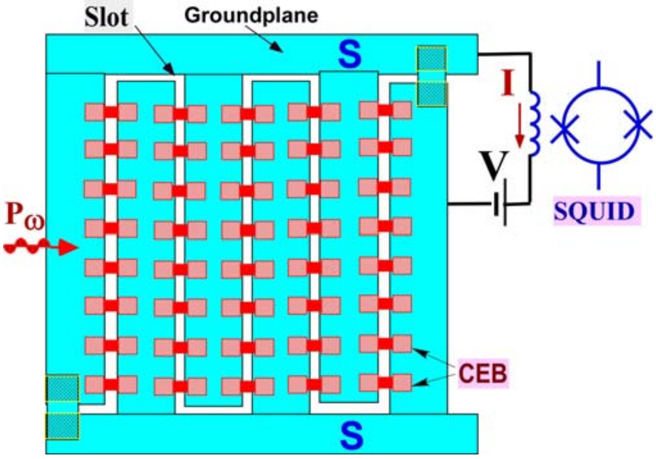

Fig 2 A distributed single polarization slot antenna [12,13] with a parallel array of Cold-Electron Bolometers (CEB) [Kuzmin] and a SQUID readout. This slot antenna will be sensitive only to horizontal component of RF signal. The CEBs with SIN tunnel junctions and Al-Al SQUID could be fabricated on the same chip in one vacuum circle [Kuzmin-patent].

We have analyzed the concept of an optimal cold-electron bolometer for 350 GHz channel of BOOMERANG balloon telescope in the presence of the typical power load (P_0 = 5 pW per polarization component) [4]).

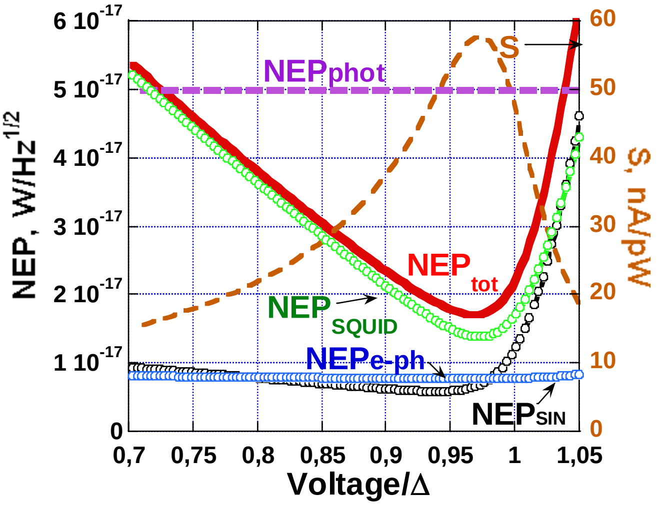

Fig. 3 Total NEP of the 40 CEB array with SIN tunnel junctions for the 350 GHz channel, with a SQUID noise current of 0.8 pA/Hz$^{1/2}$. R=0.2 kOhm, S=1μm^2, Vol=0.005um^3, power load $P_0 = 5$ pW, T=300 mK. The NEPphot= 5*10^{-17} W/Hz$^{1/2}$ is shown by dashed line.

Photon noise: $NEP_{phot} = \sqrt{2P_0 * hf}$.

(10)

For the 350GHz channel, NEPphot= 5*10^{-17} 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 of 0.8 pA/Hz$^{1/2}$. The level of NEPtot<NEPphot has been clear achieved for selected parameters of the CEB.

IV 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 series/parallel array of CEBs with SIN Tunnel Junctions, for effective matching to a JFET amplifier [8] (Fig. 7). This concept could be optimal for matching with distributed dipole antenna (Fig. 4).

Previous analysis of a single current-biased CEB with JFET readout showed that the JFET input voltage noise limits the sensitivity [8]. 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 series/parallel connection of CEBs with dipole antennas (Fig. 4). 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.

In this paper we analyze a realization of the CEB array for the 350 GHz channel of BOOMERANG. For RF coupling we analyze a system with the CEB array coupled to focal plane dipole antennas (Fig. 4). The problem of DC biasing the CEB arrays can be solved by interconnecting neighbour dipoles by a narrow strip with very high inductive impedance (Fig. 4). This dipole antenna will be sensitive only to one horizontal component of RF signal.

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.

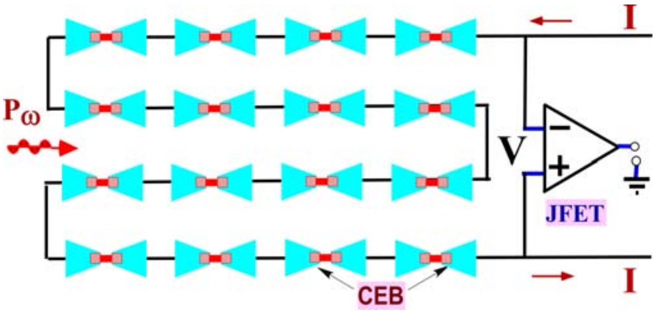

Fig 4 A distributed single polarization dipole antenna [] with a series array of CEBs [8] and a JFET readout. This dipole antenna will be sensitive only to horizontal component of RF signal.

The operation of a CEB array can be analyzed using the heat balance equation for a single CEB [16] taking into account power distribution between the N bolometers. The responsivity S_V is described by the voltage response to an incoming power

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

(10)

The second term

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

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:

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

(12)

Here NEP_{e-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]:

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

(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$^{1/2}$:

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

(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 350 GHz channel of BOOMERANG.

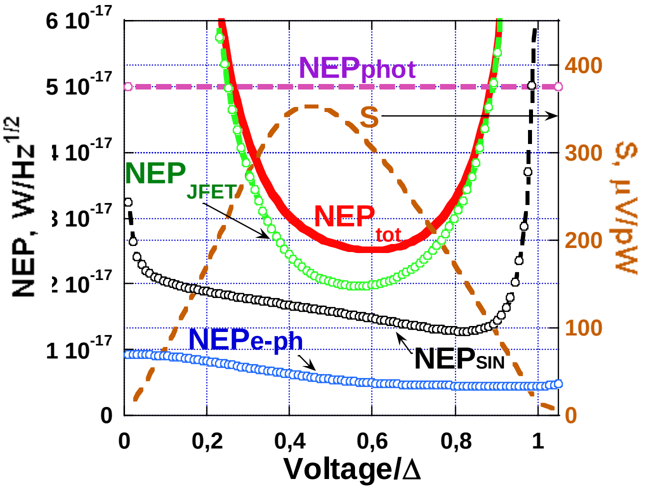

Fig. 5. NEP components of the array of 20 CEBs with JFET readout at 350 GHz with power load of 5 pW for I_{JFET}=10 fA/Hz$^{1/2}$, V_{JFET}=5 nV/Hz$^{1/2}$, R=1 kOhm, Λ=0.005µm^3, T=300 mK.

We have simulated arrays of CEBs with different numbers of CEBs, from 1 to 1000, to achieve a low NEP with JFET readout and check ability to use large number of CEBs for one pixel. Fig. 5 shows typical results of an NEP simulation for the optimal array of 20 CEBs. We see that for a range of normalized voltage from 0.27 to 0.87, 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 6. The total NEP decreases to a level less than photon noise for a number of CEBs larger than 6. It is achieved mainly through the suppression of the JFET noise component due to the increased responsivity (10). Figure 6 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=20) the NEP_{JFET} is close to NEP_{SIN} , which is the goal for 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).

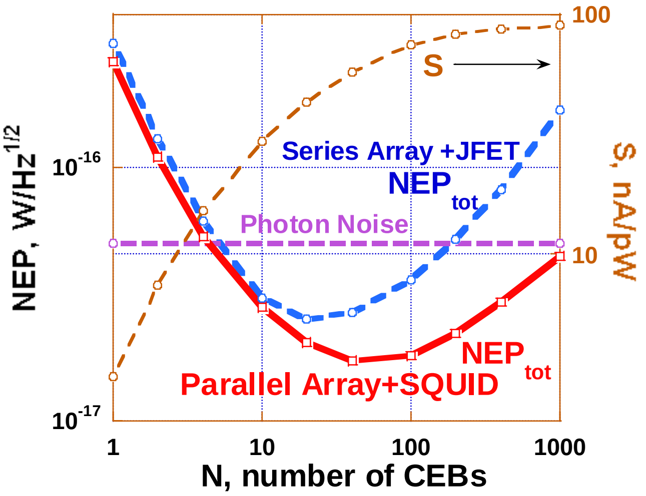

Fig. 6. NEP components and photon NEP in dependence on the number of CEBs in a voltage-biased parallel array with SQUID and in current-biased series array with JFET. The parameters of CEBs are the same as in Fig. 3 and 5. The responsivity S is shown for parallel array for illustration of the effect of 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.

CONCLUSION

We have analyzed several variations of the concept of a Cold-Electron Bolometer (CEB) with an SIN (Superconductor-Insulator-Normal Metal) tunnel junctions for matching with focal plane antenna. The parallel combination of CEBs with SQUID readout is better for distributed slot antenna. The series combination of CEBs with JFET readout is better for distributed dipole antenna. These concepts give unique opportunities to achieve NEPs less than photon noise for any optical power loading with standard JFET or SQUID readouts.

RF coupling of CEBs to distributed focal plane antennas would help to avoid more complicated matching with horns or Si lenses.

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