Superconducting Cold-Electron Bolometers with JFET Readout for OLIMPO Balloon Telescope

Leonid Kuzmin1), Phillip Mauskopf2), and Dmitry Golubev3)
1) Chalmers University of Technology, S-41296 Gothenburg, Sweden,
2) Cardiff University, United Kingdom
3) Karlsruhe Forschungszentrum, Germany
leonid.kuzmin@mc2.chalmers.se

Abstract. The OLIMPO experiment is a 2.6 m balloon-borne telescope, aimed at measuring the Sunyaev-Zeldovich effect in clusters of Galaxies. OLIMPO will carry out surveys in four frequency bands centered at 140, 220, 410 and 540 GHz. The detector system consists of four bolometer arrays and incorporates new detector technologies that are potential candidates for future space missions. One of these technologies is the Capacitively Coupled Cold-Electron Bolometer (CEB) with JFET readout. The JFET readout coupled to semiconductor-based high-impedence bolometers has been developed already for the BOOMERanG and Planck-HFI experiments. The CEB is a planar antenna-coupled superconducting detector with high sensitivity and high dynamic range. Here, we discuss a scheme to match the relatively moderate dynamic resistance of CEB (~1kOhm) to the high noise equivalent resistance of JFET (1 MΩ). To achieve noise matching with JFET, a Cold-Electron Bolometer with a weak Superconducting Absorber (SCEB) has been proposed. In voltage-biased mode with voltage higher than (Δ1-Δ2) the IV of SIS’ junctions has considerably increased dynamic resistance up to the level of Rj=1000*Rn. Electron cooling will be still very effective for the incoming power. Simulations show that photon noise level can be achieved at 300 mK for a structure with Ti absorber and Al/Ti tunnel junctions for all frequency ranges with the estimated in-flight optical power load for OLIMPO.

1. Introduction
The OLIMPO experiment is a 2.6 m balloon-borne telescope, aimed at measuring the Sunyaev-Zeldovich effect in clusters of Galaxies. The high Galactic latitude sky at far infrared (FIR) and millimetric frequencies has three main sources of diffuse emission: the Cosmic Microwave Background (CMB) with its primary anisotropy and with the Sunyaev-Zeldovich effect from Clusters of Galaxies, and the Far Infrared Background (FIRB) from early galaxies. The "cosmological window" extends roughly from 30 to 600 GHz: at lower frequencies interstellar emission of spinning dust grains, free-free and synchrotron emission from the interstellar medium dominate over the cosmological background; at higher frequencies the clumpy foreground from "cirrus clouds" of interstellar dust dominates the sky brightness. The only way to separate the sources of emission is using multi-band experiments. OLIMPO will carry out surveys in four frequency bands at 140, 220, 410 and 540 GHz. Primary CMB anisotropy will be detected in the lower frequency bands. Due to high angular resolution, OLIMPO will be able to measure the angular power spectrum of the CMB up to multipoles around 5000, significantly higher than BOOMERanG, WMAP and Planck. The measurement of the damping tail of the power spectrum will provide estimates of the dark matter density. In addition, the frequency coverage of OLIMPO will allow the large-scale SZ signal to be cleanly separated from the primary anisotropy. The amplitude of the angular power spectrum of SZ
emission at these multipoles will provide a strong constraint on the amplitude of the primordial perturbations in the matter power spectrum as well as constraining the evolution of dark energy.

The OLIMPO detector system consists of four bolometer arrays. These detectors are an evolution of the devices used in the BOOMERanG and Planck-HFI instruments. In order to achieve low dispersion in the characteristics of the detectors, a fully photo-lithographic process producing sensors on silicon nitride islands on a Si wafer will be developed. Filters and antennas can be integrated on the detector chips. The four arrays at 140, 220, 410 and 540 GHz will be composed of 19, 37, 37, 37 detectors respectively. The bolometer arrays will be mounted on a 300 mK cold stage in a cryostat that is a modified version of the BOOMERanG cryostat.

2. Detector requirements

The estimated optical loading on the OLIMPO detectors in flight determines the required detector parameters and the ultimate sensitivity of the instrument. The optical loading is dominated by emission from the warm telescope plus the emission from the 2.73 K CMB. We assume an emissivity for the OLIMPO telescope of 5%, an effective temperature of 250 K and an optical efficiency of the receiver of 30%. The power on each detector at 140, 220, 410 and 540 GHz is 4, 6, 14 and 28 pW respectively. From these values we can calculate the fundamental limit to sensitivity from photon noise and express this in terms of an NEP as well as an effective sensitivity to temperature variations either in Rayleigh-Jeans temperature (assuming the source temperature is much greater than the observation wavelength, kT >> hν) or in CMB temperature units (assuming a source temperature of 2.7 K). These parameters are given in Table 1.

| Frequency (GHz) | 150 | 220 | 410 | 540 |
|-----------------|-----|-----|-----|-----|
| Bandwidth (GHz) | 35  | 45  | 50  | 50  |
| Telescope loading (pW) | 6  | 14  | 28  |
| RJ sensitivity (μK/Hz^{1/2}) | 90 | 100 | 80 | 65 |
| CMB sensitivity (μK/Hz^{1/2}) | 160 | 300 | 2100 | 10000 |

Table 1: Optical loading and sensitivities of OLIMPO detectors

In the remainder of this paper, we use these parameters to design optimum configurations of the CEB+JFET system for each OLIMPO frequency band. We require the detectors not to saturate under 3 times the estimated optical loading and we require the detector and readout combination to contribute a noise less than the photon noise.

3. SCEB – JFET in voltage biased mode

Single CEB. Capacitively Coupled Cold-Electron Bolometer (Fig. 1) consists of planar antennae and normal metal absorber coupled by two SIN tunnel junctions [2]. The CEB can realize high sensitivity and high dynamic range in voltage-biased mode with SQUID readout. The CEB utilizes strong electron cooling for high performance and a typical dynamic resistance in an operating point is around 1 kOhm.

Previous analysis of a single CEB with a normal metal absorber and JFET readout showed that the sensitivity is limited by the JFET noise when using a voltage bias and a current readout (Figure 2). The motivation for voltage-biased mode is realization of electron cooling served as strong electrothermal feedback with corresponding improvement of signal and noise characteristics [2].

However, for the CEB with a normal metal absorber, the input voltage noise is divided by small dynamic resistance of the junctions in cooling region and gives a large noise current, limiting the sensitivity at a level higher than the photon noise in an experiment such as OLIMPO [1].

Here we analyse a single SCEB (CEB with a weak superconducting absorber, SIS’IS, [3]) with a JFET readout in voltage-biased mode. The optimum voltage bias point is between (Δ1 -
Delta 2) and (Delta1 + Delta 2). In this region the I-V of SIS junctions has considerably increased dynamic resistance, limited by fluctuations or leakage current at the level of 1000*Rn-2000*Rn (typical level of leakage in our fabrication). Electron cooling will be still very effective for incoming power.

Electron cooling will be still very effective for incoming power.

We estimate the performance of the SCEB using a theoretical model with certain simplifying assumptions [4]. We assume complete relaxation of the quasiparticle distribution function in the absorber and describe it with a single parameter – effective temperature. Josephson current is ignored since the Josephson effect can be suppressed by a relatively weak magnetic field. Within the framework of this model we calculate the Noise Equivalent Power (NEP) of a single SCEB with JFET readout for the lowest frequency channel in the OLIMPO experiment and show that they satisfies the requirements for sensitivity and dynamic range. One drawback of the SCEB compared to the CEB is the increase in the electronic shot noise due to the increased level of energy quantization, ($\Delta_1$ instead of $kT_e$ for a normal metal absorber [2]) and corresponding decrease in current responsivity as the number of electrons per photon is given by $N = \frac{h}{\Delta_1}$. The improvement due to the suppression of the large voltage noise of the JFET, however, is larger than this increase in the shot noise.

Current fluctuations of JFET could be rather low and would be determined by feedback resistor. For 100 MOhm at 4K the current noise will be at the level of 5 fA/Hz$^{1/2}$.

**1. Channel I: "2.1 mm" (150 GHz)** The lowest frequency channel of OLIMPO has the lowest optical power loading, $P_0 = 2$ pW, and lowest corresponding photon noise, $NEP_{phot} = \sqrt{\frac{2P_0}{h\nu} \Delta f}$.

$NEP_{phot} = 2 \times 10^{-17} W/Hz^{1/2}$. Figure 3 shows calculation of the different contributions to the total NEP of the detector for an optimized geometry (volume of the absorber) and different normal resistances ($R_n$) of the tunnel junctions. We see that for a range of bias voltages and values of $R_n$, the total NEP of the SCEB is less than photon noise: $NEP_{tot} < NEP_{phot}$. In addition, the $NEP_{tot}$ of the SCEB is dominated by shot noise ($NEP_{SIS}$) in the detector current corresponding to power removed from the superconducting absorber through the tunnel junctions (in contrast to the normal metal CEB where JFET noise clearly dominates).
Fig. 3. Total NEP for SCEB, total $i_{JFET}=10 \text{ fA/Hz}^{1/2}$, $R=0.5 \text{ kOhm}$ and $0.1 \text{ kOhm}$, Vol=$0.05 \text{um}^3$, power load – $2 \text{ pW}$. IV curves are shown for estimation of high dynamic resistance of the junctions.

Fig. 4. NEP components for SCEB with JFET readout for $i_{JFET}=10 \text{ fA/Hz}^{1/2}$, $R=0.2 \text{ kOhm}$ (one junction), Vol=$0.1 \text{um}^3$, power load – $2 \text{ pW}$. IV curve is shown for estimation of high dynamic resistance of the junctions.

**Ideology of the SCEB - JFET matching:** For typical values of JFET noise: $5 \text{ nV/Hz}^{1/2}$ and $5 \text{ fA/Hz}^{1/2}$, the JFET has an effective noise impedance around $1 \text{ MOhm}$. A typical dynamic resistance of a CEB at the optimum operating bias voltage (near the gap voltage for strong electron cooling) is around $1 \text{ kOhm}$ or about three orders of magnitude lower than the JFET noise impedance. Replacing the CEB with a SCEB (with weak superconducting absorber) we can choose a flat region of IV curve with very high dynamic resistance. The increase of the dynamical resistance will be limited by leakage resistance (or gap smearing) and is just about the 3 orders of magnitude needed for optimum noise-matching conditions. This scheme can be successfully implemented for all channels of OLIMPO by changing the junction normal resistances.

4. Series array of CEBs in current-biased mode

An alternate mode of operation of the CEB is using a current bias and a voltage readout. Previous analysis of a single current-biased CEB with JFET readout showed that the JFET input voltage noise once again severely limited the sensitivity[2]. Typical results for current-biased mode can be seen in Fig. 3 for N=1 (single bolometer). The main reason is degradation of voltage responsivity under high optical power loading. The only chance to achieve photon noise level is to use an array of bolometers in series. In this case the input power is divided between each bolometer and they retain high responsivity while the output signal is collected from all bolometers. In the case of a lumped element absorber coupled to a single antenna this could be realized as a parallel connection of bolometers for RF and a series connection for DC. In the case of a distributed antenna or array of slot antennas for a single pixel, it could be realized naturally as series connection of bolometers for both DC and RF signals.

**Channel I: "2.1 mm" (150 GHz).** Power load is relatively high: $P_0 = 2 – 3 \text{ pW}$.

Photon noise: $NEP_{phot} = \sqrt{2P_0 \cdot hf}$, $NEP_{phot} = 2 \times 10^{-17} W/Hz^{1/2}$. Once again, the total NEP of the detector+readout should be less than photon noise: $NEP_{tot} < NEP_{phot}$. For current-biased mode, only an array of CEBs can achieve a low enough NEP using a JFET readout.
Fig. 5. a) Series connection of CEBs in coplanar line. Array of 8 CEBs for 4 coplanar lines of one circular waveguide will be connected in series.

**Optimal number of CEBs in series array.** The general rule of array design is the following: Number of bolometers, N, should be increased to split Po between bolometers but up to the moment when \( P_o/N = P_{ph} \), where \( P_{ph} = T_{ph}^6 \), \( T_{ph} \) - temperature, \( V \) - voltage. The phonon power is determined by only one parameter, the volume of the absorber. There is no need to increase number of bolometers more than this figure because the optical power loading in each bolometer becomes less than the power from phonons. The volume of each device in the array should be decreased as much as possible to decrease this figure (in contrast to SQUID readout where resistance of the junctions is the most important). For the higher power channels (e.g. 600 GHz), the use of array is more effective than for lower power channels (e.g. 140 GHz).

Fig. 6. Total NEP of CEB and NEPphot for series array of CEBs in dependence on number of CEBs a) 600 GHz, power load \( P_o = 20 \) pW, \( v_{JFET} = 3 \) nV/Hz\(^{1/2} \), \( R = 0.5 \) kOhm (one junct.), \( Vol = 0.05 \mu m^3 \). Optimal number of bolometers is 30-50. b) 140 GHz, \( P_o = 2 \) pW, \( v_{JFET} = 2 \) nV/Hz\(^{1/2} \), \( R = 0.5 \) kOhm (one junct.), \( Vol = 0.02 \mu m^3 \). Optimal number of bolometers is 5-10.

5. Conclusions

For typical values of JFET noise: 5 nV/Hz\(^{1/2} \) and 5 fA/Hz\(^{1/2} \), the JFET has an effective noise impedance around 1 MOhm. The typical dynamical resistance of a CEB at the optimum operating point (near the gap for strong electron cooling) is around 1 kOhm. Replacing the CEB with a SCEB (with weak superconducting absorber) we can choose a voltage bias in the flat region of the IV curve with very high dynamic resistance. Increase of resistance will be limited by leakage resistance and is approximately 3 orders of magnitude, enough for noise-matching conditions. This configuration can give photon noise limited performance at 300 mK base temperature over a wide range of optical loading conditions. Another possibility for high background measurements is to use a current-biased series array of CEBs with normal metal absorbers.

[1] S. Masi et al., OLIMPO: a balloon-borne, arcminute-resolution survey of the sky at mm and sub-mm wavelengths , in 16th ESA Symposium on European Rocket and Balloon Programmes, June 2-5, 2003, St.Gallen (2003), ESA-SP-530, 557-560
[2] L. Kuzmin “Ultimate Cold-Electron Bolometer with Strong Electrothermal Feedback”, Proc. of SPIE conference “Millimeters and Submillimeter Detectors”, 5498, p 349, Glasgow, June 21, 2004.
[3] Leonid Kuzmin, “Superconducting Cold-Electron Bolometer with Proximity Traps”, Microelectronic Engineering, 69, 309-316 (2003).
[4] D. Golubev, L. Kuzmin ‘Cold-electron bolometer with superconducting absorber’, Proc. of the 9 Int. Workshop “From Andreev Reflection to the Earliest Universe”, Bjorkliden, Sweden, April 2005