Abstract

This work presents the integration of the Cold-Electron Bolometer (CEB) in Frequency Selective Surface (FSS) forming a distributed absorber and is aimed towards balloon-borne telescope missions with high background power requirements (typically tens of pW). FSS are frequency sensitive structures typically consisting of a simple repeating pattern that is impedance matched to incident electromagnetic radiation. We have investigated the integration of CEB detectors in the FSS and their response to incident millimeter/submillimeter radiation. The inherent frequency sensitive characteristics of the FSS allow these kinds of arrays to be designed for a wide range of frequency bands with coupling efficiencies approaching unity. The CEBs act as a distributed absorber distributing the power load over all the bolometers, reducing overheating and improving responsivity.

We have developed a 23 pixel CEB array at 345 GHz and 480 GHz for the OLIMPO telescope for performing photometric and spectroscopic observations of the Sunyaev– Zel’dovich effect from clusters of galaxies. Measurements from 345 GHz test pixels indicate a responsivity up to $2 \times 10^8$ V/W at low background powers. Spectral measurements indicate a bandwidth of about 20 GHz. Using room temperature commercial amplifiers, the Noise Equivalent Power was estimated as $2 \times 10^{-16} \text{ W/}\sqrt{\text{Hz}}$, which is larger than the theoretically modelled value by a factor of 4-5. Prototype pixels which could possibly be used for the 145 GHz and 95 GHz channels on the SWIPE instrument in the LSPE balloon-borne telescope have also been developed and characterised. The spectral response of the 95 GHz pixel closely matches RF simulations with a bandwidth of about 8 GHz. An efficiency greater than 70% is estimated from analysis of measured data with responsivity approaching $1 \times 10^8$ V/W at a background power of 60 pW. Photon noise limited operation can be achieved with the use of low noise cold JFET amplifiers and these high sensitivities at high background power loads.

Keywords: Cold-Electron Bolometer, Frequency Selective Surface, mm-wave detectors, Focal Plane array, OLIMPO, LSPE
List of Publications

This Thesis is based on the work contained in the following papers:

1. A Frequency Selective Surface based focal plane receiver for the OLIMPO balloon-borne telescope
   Mahashabde, S., Sobolev, A., Bengtsson, A., Andrén, D., Tarasov, M.A., Salatino, M., de Bernardis, P., Masi, S., & Kuzmin, L.S.

2. Planar Frequency Selective Bolometric Array at 350 GHz
   Mahashabde, S., Sobolev, A., Tarasov, M.A., & Kuzmin, L.S.

3. A distributed-absorber Cold-Electron Bolometer single pixel at 95 GHz
   Mahashabde, S., Tarasov, M.A., Salatino, M., Sobolev, A., Masi, S., Kuzmin, L.S. & de Bernardis, P.
   Submitted

4. Power Load and Temperature Dependence of Cold-Electron Bolometer Optical Response at 350 GHz
Tarasov, M.A., Edel’man, V.S., Mahashabde, S., & Kuzmin, L.S.

5. Optical Response of a Cold-Electron Bolometer Array Integrated in a 345-GHz Cross-Slot Antenna

Tarasov, M. A., Kuzmin, L. S., Edel’man, V. S., Mahashabde, S., & de Bernardis, P.
Other Publications

1. Nonthermal optical response of superconductor-insulator-normal metal-insulator-superconductor tunnel structures

   Tarasov, M. A., Edel’man, V. S., Mahashabde, S., & Kuzmin, L. S.

   Journal of Experimental and Theoretical Physics, Volume 119, Issue 1, pp 107-114 (2014)

2. Quantum Efficiency of Cold Electron Bolometer Optical Response

   Tarasov, M. A., Edel’man, V. S., Ermakov, A. B., Mahashabde, S., & Kuzmin, L. S.


3. Sensitivity to Cosmic Rays of Cold Electron Bolometers for Space Applications

   Salatino, M., de Bernardis, P., Kuzmin, L. S., Mahashabde, S., & Masi, S.


4. Express Optical Analysis of Epitaxial Graphene on SiC: Impact of Morphology on Quantum Transport


   Nano Letters, 13(9), 4217-4223 (2013)

5. Cold-electron bolometers for future mm and sub-mm sky surveys

   Salatino, M, de Bernardis, P, Mahashabde, S., Kuzmin, L. S., & Masi, S.

- Sumedh Mahashabde, 2015
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<td>Ag</td>
<td>Silver</td>
</tr>
<tr>
<td>Al</td>
<td>Aluminium</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>Aluminium Oxide</td>
</tr>
<tr>
<td>BCS</td>
<td>Bardeen, Cooper, Schrieffer</td>
</tr>
<tr>
<td>BWO</td>
<td>Backward Wave Oscillator</td>
</tr>
<tr>
<td>CAD</td>
<td>Computer-aided Design</td>
</tr>
<tr>
<td>CEB</td>
<td>Cold-Electron Bolometer</td>
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<tr>
<td>CMB</td>
<td>Cosmic Microwave Background</td>
</tr>
<tr>
<td>Cs</td>
<td>Caesium</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DRIE</td>
<td>Deep Reactive Ion Etch</td>
</tr>
<tr>
<td>ETF</td>
<td>Electrothermal Feedback</td>
</tr>
<tr>
<td>FSS</td>
<td>Frequency Selective Surface</td>
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<tr>
<td>HEB</td>
<td>Hot-Electron Bolometer</td>
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<tr>
<td>HFSS</td>
<td>High Frequency Structure Simulator</td>
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<td>InSb</td>
<td>Indium Antimonide</td>
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<td>IV</td>
<td>Current-Voltage Characteristics</td>
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<tr>
<td>JFET</td>
<td>Junction Field Effect Transistor</td>
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<tr>
<td>KID</td>
<td>Kinetic Inductance Detector</td>
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<tr>
<td>LSPE</td>
<td>Large-Scale Polarization Explorer</td>
</tr>
<tr>
<td>NDF</td>
<td>Neutral Density Filter</td>
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<tr>
<td>NEP</td>
<td>Noise Equivalent Power</td>
</tr>
<tr>
<td>NET</td>
<td>Noise Equivalent Temperature</td>
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<td>NHEB</td>
<td>Normal Metal Hot-Electron Bolometer</td>
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<td>Abbreviation</td>
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<td>--------------</td>
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<tr>
<td>NIS</td>
<td>Normal Metal-Insulator-Superconductor</td>
</tr>
<tr>
<td>NS</td>
<td>Normal-Superconductor</td>
</tr>
<tr>
<td>NTD-Ge</td>
<td>Neutron Transmutation Doped Germanium</td>
</tr>
<tr>
<td>OLIMPO</td>
<td>Osservatorio nel Lontano Infrarosso Montato su Pallone Orientabile</td>
</tr>
<tr>
<td>PCB</td>
<td>Printed Circuit Board</td>
</tr>
<tr>
<td>PECVD</td>
<td>Plasma Enhanced Chemical Vapour Deposition</td>
</tr>
<tr>
<td>ppm</td>
<td>Parts per Million</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RPM</td>
<td>Rounds per Minute</td>
</tr>
<tr>
<td>sccm</td>
<td>Standard Cubic Centimeters per Minute</td>
</tr>
<tr>
<td>SINIS</td>
<td>Superconductor-Insulator-Normal Metal-Insulator-Superconductor</td>
</tr>
<tr>
<td>SQUID</td>
<td>Superconducting QUantum Interference Device</td>
</tr>
<tr>
<td>STJ</td>
<td>Superconducting Tunnel Junction</td>
</tr>
<tr>
<td>TES</td>
<td>Transition Edge Sensor</td>
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<thead>
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<tr>
<td>$\beta$</td>
<td>Fraction of power returning from the superconductor to the normal metal</td>
</tr>
<tr>
<td>$\delta P$</td>
<td>Signal power</td>
</tr>
<tr>
<td>$\delta P_0$</td>
<td>Background power</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Dynes parameter</td>
</tr>
<tr>
<td>$\Lambda_S$</td>
<td>Volume of superconducting electrode</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>Volume of normal metal</td>
</tr>
<tr>
<td>$\nu(E)$</td>
<td>Dynes density of states</td>
</tr>
<tr>
<td>$\nu_0$</td>
<td>Normalised density of states in a superconductor</td>
</tr>
<tr>
<td>$\Sigma$</td>
<td>Electron-phonon coupling constant in the normal metal</td>
</tr>
<tr>
<td>$\Sigma_S$</td>
<td>Electron-phonon coupling constant of superconductor</td>
</tr>
<tr>
<td>$\tau_{e-e}$</td>
<td>Electron-electron relaxation time</td>
</tr>
<tr>
<td>$\tau_{e-ph}$</td>
<td>Electron-phonon relaxation time</td>
</tr>
<tr>
<td>$\Delta$</td>
<td>Energy gap of a superconductor</td>
</tr>
<tr>
<td>$^3\text{He}$</td>
<td>Helium-3</td>
</tr>
<tr>
<td>$E$</td>
<td>Energy</td>
</tr>
<tr>
<td>$e$</td>
<td>Electron charge</td>
</tr>
<tr>
<td>$f_N(E)$</td>
<td>Fermi function in a normal metal</td>
</tr>
<tr>
<td>$f_S(E)$</td>
<td>Fermi function in a Superconductor</td>
</tr>
<tr>
<td>$h$</td>
<td>Planck constant</td>
</tr>
<tr>
<td>$I$</td>
<td>Current</td>
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Abbreviations and Notations

\[ i \] Imaginary number, \( \sqrt{-1} \)
\[ I_c \] Critical current of a superconducting electrode
\[ I_n \] Current noise spectral density
\[ k_B \] Boltzmann constant
\[ P_N \] Power deposited in normal metal
\[ P_S \] Power deposited in superconducting electrode
\[ R_a \] Resistance of the absorber
\[ R_N \] Normal state resistance of a tunnel junction
\[ S_I \] Current responsivity
\[ S_V \] Voltage responsivity
\[ T_c \] Critical temperature of a superconductor
\[ T_e \] Electron temperature in a normal metal
\[ T_{ph} \] Phonon Temperature
\[ T_{qp} \] Quasiparticle temperature
\[ V \] Voltage
\[ V_n \] Voltage noise spectral density
\[ \nu \] Frequency
\[ M \] Number of CEBs in series
\[ QP \] Quasiparticles
\[ S_{11} \] Input return loss
\[ W \] Number of CEBs in parallel
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Introduction

Human beings have stared at the stars in the night sky since time immemorial. The science of optical astronomy developed as a result of human curiosity to learn the origin of these heavenly sources of light. The human eye was the only instrument employed for celestial observations but the early astronomers had managed to distinguish immovable stars from “wandering” planets. Eclipses were studied and an understanding of the motion of the Sun and the Moon was developed. The development of telescopes and mathematics aided astronomers in their quest to describe the motion of planets. Telescopes also revealed the fuzzy looking galaxies, nebulae and the occasional comet. The advent of spectroscopy enabled the discovery of chemical elements in the Sun and distant stars. In the latter half of 20th century, the understanding of electromagnetic spectrum gave rise to celestial observations in different frequency bands. Development of radio astronomy enabled the study of strong radio sources in the Milky Way galaxy and beyond. Extremely powerful sources like pulsars and quasars were discovered and studied. The Cosmic Microwave Background (CMB) was also discovered pervading the night sky at millimeter and submillimeter frequencies.

Discovered in 1964, the CMB is an object of intense study even today. CMB photons, initially emitted at about 3000 K at the last scattering event, are now redshifted due to expansion of the universe and are described by Planck distribution of $2.725 \pm 0.002$ K peaking at 160 GHz.
Chapter 1. Introduction

[1]. The CMB was emitted when universe became transparent to radiation and is a snapshot of the universe when it was about 380000 years old. It provides an important confirmation of the Standard Cosmological Model and of the thermal history of our Universe.

The tiny anisotropies (order of 30 ppm) in the CMB spectrum explains the structure formation (galaxy clusters, galaxies, stars, etc) we observe today. The inflationary process is predicted to have left imprints in the form of a tiny polarization in the CMB. Detecting this polarised signal in the CMB will provide a confirmation of the inflation theory. However, this detection is complicated by the contamination of the CMB spectrum by synchrotron radiation and interstellar dust.

A large number of ground based, balloon-based and space-based missions have studied the CMB over the past three decades. The most famous early measurements of the CMB were made by National Aeronautics and Space Administration (NASA)’s COsmic Background Explorer (COBE) satellite using the FIRAS instrument [1] demonstrating the Planckian nature of the CMB spectrum. The balloon-borne BOOMERAnG experiment [2] and NASA’s WMAP satellite [3] further measured the power spectrum at angular scale of about 1°. The European Space Agency (ESA) Planck Surveyor satellite launched in 2009 [4] has produced the highest resolution map of the CMB to date.

Satellite missions like Planck are able to measure the power spectrum up to very large angular scales since they are able to map the whole sky. The disadvantage is that such missions are expensive and short lived; Planck operated for about 2.5 years until its coolant supply ran out and the cryogenic detectors warmed up. Ground based telescopes have a much longer lifetime and there exists a possibility for their detectors to be upgraded. The disadvantage is that ground based instruments are blind to a large portion of the electromagnetic spectrum due to absorption by water molecules in the atmosphere. Balloon-borne missions on the other hand can fly to altitudes of 30 km or above where the water content in the atmosphere is low enough to permit observations in the submillimeter spectrum. The long duration stratospheric balloon can fly for a period of up to 100 days while the telescope and the detectors suspended in the gondola beneath it can perform measurements. In most cases, the balloon, telescope and data can be recovered after the balloon lands. Moreover, since the signature from inflation is expected at angular scales of the order of 1°, there is not much advantage in observing from space since a balloon-borne experiment can survey the sky with comparable resolution compared to a
satellite on these angular scales at a fraction of the cost.

After the success of the BOOMERanG mission in 1999, several balloon-borne missions have been proposed to measure different aspects of the CMB. The balloon missions MAXIMA [5], Archeops [6], BOOMERanG-II [7], EBEX [8], SPIDER [9] and future missions like OLIMPO [10], LSPE [11] and PIPER [12] demonstrate the popularity of these cheap (relative to satellites) missions with a fast turnaround time. Most of these missions used either NTD-Ge thermistors or spider-web bolometers with a Transition Edge Sensor (TES). The large inherent bandwidth of these bolometers made it possible to use the same type of devices in different frequency bands with the bandwidths chosen by metal mesh quasioptical filters. These devices were generally operated at 100 mK or 300 mK depending on the type of cryocooler used and the number of pixels is of the order of 1000s.

Currently, the world of ultra high sensitivity superconducting bolometers is dominated by the TES [13]. This device operated on the principle of a voltage biased superconducting film heated to its superconducting transition temperature. A change in incident power is translated to a change in the current through the device which can be measured. Along with balloon-borne telescopes, this bolometer has been used in ground based telescopes where large arrays (thousands of pixels or more) have been successfully commissioned [14]. Another ultra sensitive bolometer is the Kinetic Inductance Detector (KID) [15]. This detector is a superconducting resonator with a resonance frequency which is usually designed in the frequency band 4-12 GHz. Incident radiation breaks Cooper pairs in the resonator changing the resonance frequency due to a change in the surface impedance of the resonator. KIDs use a frequency domain readout allowing for very high density multiplexing. Thousands of KIDs can be read out by a single coaxial line making it very attractive to be used in instruments with large arrays. Superconducting Tunnel Junctions (STJ) detectors are also a popular direct detector [16]. When a high energy photon is incident on an electrode of a STJ, it breaks a Cooper pair in the electrode. The resulting quasiparticles cause a change in the current across the junction which can be detected.

The detector used in this work is the Cold-Electron Bolometer (CEB) [17]. This device operates on the principle of heating of a very small volume of a normal metal by incident electromagnetic radiation and reading out the increase in temperature by a Normal Metal-Insulator-Superconductor (NIS) tunnel junction. The readout also causes the cooling of electron
system of the absorber which improves its dynamic range and responsivity. The electron cooling also helps to increase the saturation power of the bolometer.

Outline of the thesis

This thesis describes the design, fabrication and characterisation of a planar, photometric bolometer array for the OLIMPO balloon-borne telescope for the 345 GHz and 480 GHz frequency bands. This distributed absorber architecture is based on the Frequency Selective Surface which defines the spectral bandwidth of the bolometric array. Prototype devices at 145 GHz and 95 GHz are also fabricated, studied and described here.

Chapter 2 describes the Cold-Electron Bolometer. The theoretical model is presented along with the description of most important characteristics like responsivity and noise. Chapter 3 describes the design of the Frequency Selective Surface and integration of bolometric detectors within it. Chapter 4 describes the electrical characterisation of CEBs integrated in the FSS fabricated for the OLIMPO and the LSPE balloon-borne telescopes. Chapter 5 describes studies of the DC properties of the CEB. This chapter also describes experiments with high sensitivity thermometers fabricated using a technology similar to the CEB. This thesis is summarised in Chapter 6 with a look at future prospects of this type of detector arrays.
The Cold-Electron Bolometer

This chapter describes the Cold-Electron Bolometer [17, 18]. The CEB is a promising superconducting bolometer comparable in sensitivity to the well established Transition Edge Sensor and the Kinetic Inductance Detector. The theoretical model of the CEB is presented along with latest modifications. The DC and RF properties are also presented. This will give the reader an idea of the capabilities of this direct detector. A simple cartoon of the CEB is presented in Fig. 2.1. High resolution images of a fabricated CEB are shown in Fig. 2.2.

2.1 Basic Concepts

The CEB is an ultrasensitive superconducting direct detector. The detector has a Superconductor-Insulator-Normal Metal-Insulator-Superconductor - (SINIS) structure working on the principles of the hot electron effect, negative electrothermal feedback and electron cooling by the use of two Normal Metal-Insulator-Superconductor (NIS) junctions. Most modern high sensitivity radiation detectors including the CEB rely on the heating of a very small volume of absorbing material to which the radiation is coupled (either to the electron system or the phonon system). This changes the resistance or other physical properties of the absorber. This change can be electrically detected by a thermometer and the absorbed power can be calculated if the
transfer function of the device is known. The absorbing volume is connected to the environment through very low thermal capacity connections to reduce the leakage of heat (information) and keep the absorber “hot” long enough for the change to be read out.

![Schematic of a Cold-Electron Bolometer](image)

**Figure 2.1**: Schematic of a Cold-Electron Bolometer.

To detect very low power levels common to sources of astronomical origin, most modern detectors employ the phenomenon of superconductivity. Lowering the temperature of the absorber and the thermometer is essential to reduce the impact of thermal fluctuations on the measurement. The tiny astronomical signal can be easily lost within the thermal fluctuations if the absorbed signal power is comparable to these fluctuations. Modern detectors employ different phenomenon found in superconducting materials; sharp transition to zero resistance state (TES, HEB), Cooper pair breaking (STJ), kinetic inductance (KID) and electron tunnelling (CEB).

In case of the currently used technology for the fabrication of the CEB, the absorber is a thin film of a bilayer of Iron/Aluminium 0.7/14 nm thick and about 0.025 $\mu$m$^3$ in volume. This bilayer is not superconducting at the temperature of operation. The length of a typical NIS junction is 2 $\mu$m and the width is 0.4 $\mu$m. The superconducting electrodes of the NIS tunnel junction are made from aluminium at least 150 nm thick. Thin film aluminium has its superconducting critical temperature $T_c$ around 1.4 K. The rule of thumb in deciding the bath temperature $T_{ph}$ is $T_{ph} \leq T_c/4$. At this temperature the superconducting gap ($\triangle$) is fully formed. Thus the CEB can be used at temperatures of about 300 mK and lower, usually on the cold stage of a $^3$He sorption pump cooler. The following subsections present the properties of superconductors and normal metals.
2.1. Basic Concepts

2.1.1 Superconducting Energy Gap ($\Delta$) and Density of States

Superconductivity was discovered by Kammerlingh Onnes in 1911. Below a critical temperature $T_c$, a superconducting material completely loses its electrical resistance. Other interesting properties of the superconducting state include the Meissner effect where magnetic field is expelled from a material as it is cooled below $T_c$.

The microscopic theory of superconductivity was given by Bardeen, Cooper and Schrieffer (BCS) in 1959 [19]. The complete lack of electrical resistance is explained by the introduction of “Cooper Pairs” - electrons overcome the Coulomb repulsion to form pairs via interactions with the crystal lattice of the material. Electrical current in a superconductor is carried by these Cooper pairs (up to a critical value $I_c$) without any dissipation (zero resistance). The electron-electron interaction is mediated by phonons which are lattice vibrations moving at the speed of sound in the material. Only electrons with a certain energy near the Fermi energy of the material and opposite momentum and spin can form pairs. Below $T_c$, a “gap” opens up in the continuous spectrum of electron energies around the Fermi level. This is called the Superconducting Gap ($\Delta$) and no single electron states are present within this gap. At zero temperature, pairs of electrons at the Fermi level with opposite spin and momentum condense as Cooper pairs. At a finite temperature, single electron excitations can exist with energy larger than the energy gap. These excitations are called “quasi-particles” to distinguish them from normal electrons since these excitations cannot exist in the forbidden energy region.

Figure 2.2: (a) A scan from an atomic force microscope of a Cold-Electron Bolometer. (b) A scanning electron image of the same device. The scale bar is 200 nm.
If \( N \) is the two spin density of states at the Fermi level in the superconducting material above \( T_c \), then from BCS theory the superconducting density of states is \( N(E) = N \times \nu_0(E) \), where \( \nu_0 \) is the normalised Density of States (DOS) at \( T = 0 \) K

\[
\nu_0(E) = \left| \mathbb{R} \frac{E/\Delta}{\sqrt{(E/\Delta)^2 - 1}} \right|. \tag{2.1}
\]

From Eq. (2.1), one realises that at the gap energy \( E = \Delta \), the superconducting DOS exhibits a singularity with no states below the gap. In practice, measurements indicate existence of a finite number of states within the gap, giving rise to a finite subgap conductance. A model proposed in 1978 by Dynes et al. \[20\] is generally used in calculations involving a DOS different from the BCS DOS. This “Dynes DOS” introduces a dimensionless parameter \( \gamma \) that acts as an imaginary part of the BCS gap. The value of this dimensionless parameter is dependent on the environment of the superconductor \[21, 22\]. Data analysis of CEB measurements in the course of this work suggests that the value of \( \gamma \) is usually in the range of \( 5 \times 10^{-5} \) to \( 5 \times 10^{-3} \). The Dynes DOS used in all the calculations in this thesis is given by

\[
\nu(E) = \left| \mathbb{R} \frac{E/\Delta - i\gamma}{\sqrt{(E/\Delta - i\gamma)^2 - 1}} \right|. \tag{2.2}
\]

### 2.1.2 Normal metal and the Fermi Function

The absorber in a CEB is a normal metal, meaning that at the temperature of operation it is not superconducting. The distribution of electrons in a normal metal follows the Fermi function \( f_N(E) \), which describes the number of occupied energy states at the energy \( E \) above or below the Fermi energy level. This function is evaluated at a temperature \( T_e \) which describes the effective electron temperature in the normal metal. At equilibrium, the electron temperature \( T_e \) is expected to be equal to the bath temperature \( T_{ph} \), and the Fermi function is given by

\[
f_N(E) = \frac{1}{e^{(E/\kappa_B T_e)} + 1}. \tag{2.3}
\]
2.2 The Hot Electron Effect

“Hot electrons” are electrons whose distribution in a normal metal could be described with an effective temperature greater than the equilibrium lattice temperature. This effect was first described in semiconductors and was used to construct the first hot electron millimeter and submillimeter wavelength detectors using indium antimonide (InSb) [23, 24, 25]. Incident radiation on the piece of semiconductor would be absorbed by free carriers increasing their temperature and mobility. A similar effect can be observed in metals including superconductors. Any interaction of a photon and an electron in a metal leads to absorption of energy of the photon of frequency $\nu$ by the electron which increases its energy by $h\nu$. At low temperatures, the electron-phonon coupling is weak and this “hot electron” can exchange its energy with other electrons through electron-electron coupling. The time constant of the electron-phonon interaction, $\tau_{e-ph}$, is much larger than electron-electron time constant $\tau_{e-e}$. Thus an electron distribution with an elevated effective temperature can be established. Schematically, it is shown in Fig. 2.3. The normal metal in the SINIS structure can get heated due to incident radiation and this elevated electron temperature can be read out by the superconductor’s DOS by applying a voltage bias and tunnelling these “hot electrons” as shown in Fig. 2.4(b). The superconductor has a large number of empty states at the gap energy that electrons from the normal metal can tunnel into when a voltage bias is applied. Due to the higher energy of the hot electrons, they tunnel preferentially and the magnitude of the tunnelling current is proportional to the number of these hot electrons. Thus the NIS tunnelling current allows a readout of the electron temperature of the normal metal.

2.3 Negative Electrothermal Feedback and Electron Cooling

The use of a NIS junction as a thermometer was demonstrated in the 1970s [26]. This involved using aluminium (Al) as the superconducting element, aluminium oxide (Al$_2$O$_3$) as the tunnel barrier and silver as the normal metal. The electron temperature of the Ag was read out by the Al superconductor using NIS tunnelling. One of the first devices to use a NIS “thermometer” to probe the temperature of a normal metal absorber for
Figure 2.3: Energy diagram of the SINIS structure.

Electromagnetic radiation was the device later called the *Normal Metal Hot-Electron Bolometer* (NHEB) [27]. The NHEB described in [27] used *Normal-Superconductor* (NS) Andreev contacts to thermally isolate a normal metal volume from the environment, while simultaneously coupling submillimeter radiation to the resistive normal absorber. The increase in temperature was detected by a NIS tunnel junction. The reported sensitivity of the device was of the order of $10^9 \frac{V}{W}$.

The mechanism of *Electrothermal feedback* (ETF) was first described in 1995 by K. Irwin during the development of the TES detector [28]. A thin superconducting film is cooled to a bath temperature lower than its $T_c$, and is biased at its superconducting transition temperature using a voltage bias to dissipate power in the film. Incident radiation dissipating in the now resistive film causes an increase in temperature (and resistance) of the film. This causes a decrease in the power dissipated due to the voltage bias and subsequently decreases the temperature of the film bringing it back to its original operating point. The current flowing through the device is then proportional to the incident power which can be measured with a *Superconducting Quantum Interference Device* (SQUID). Thus the ETF increases the dynamic range and linearity of the TES.

In the CEB, ETF happens due to electron cooling. Assuming that incident radiation heats up the electron system of the absorber normal metal, and the NIS structure is biased slightly below the gap of the superconducting electrode, the tunnelling current will remove hot electrons from
the normal metal which lie in the high energy tail of the Fermi-Dirac distribution Fig. 2.4(b). The removal of hot electrons cools the normal metal. In a voltage biased CEB, the current through the NIS junctions adjusts itself depending on the electron temperature of the normal metal. Similarly, in a current bias mode, the voltage across the junctions is proportional to the electron temperature of the normal metal. The electron cooling provides the necessary feedback so that the operating point of the device is held constant preventing saturation or thermal runoff. At the correct bias, the electron system can be cooled to a point lower than the phonon system due to weak electron-phonon coupling. This increases the sensitivity of the device and decreases noise due to electron-phonon interactions.

The TES has a specific limit on the detected signal power. An increase in signal power leads to a decrease in the DC power dissipated in the device. Thus the maximum signal power that can be handled by a TES is equal to the DC heating required to hold the TES at its superconducting transition. A CEB, in contrast, has no such limitation since the tunnelling current removes the signal power. At low signal power, the cooling power balances the heating due to the signal. When the signal power becomes larger than the cooling power, the electron temperature of the CEB starts increasing, which decreases the responsivity. But a thermal runoff (or a saturation) cannot occur until the electron temperature reaches the critical temperature of the superconductor, destroying the NIS nonlinearity. An example of the IV characteristics of the CEB is shown in Fig. 2.10(a).

2.4 The Cold-Electron Bolometer model

This section describes the theoretical model of the CEB. Unless otherwise noted, the factor 2 in most equations arises from the fact that there are two NIS junctions in the CEB. Also, all the equations described in this chapter are time independent versions of the CEB equations.

2.4.1 NIS tunnelling

Current

Energy diagrams of a NIS junction in unbiased and biased states are shown in Fig. 2.4. We can begin analysing the CEB by considering a single NIS junction characteristics before analysing the full SINIS structure. The current through the NIS junction can be described by
Chapter 2. The Cold-Electron Bolometer

\[ I = \frac{1}{eR_N} \int_{-\infty}^{\infty} \nu(E)(f_N(E - eV) - f_S(E))dE, \]  

(2.4)

where \( e \) is the electron charge, \( R_N \) is the normal state resistance of the junction, \( V \) is the voltage across the junction, \( \nu(E) \) is the Dynes DOS for the superconductor, \( f_S(E) \) is the Fermi-Dirac distribution of electron (quasiparticle) system in the superconducting electrode, and \( f_N(E) \) is the Fermi-Dirac distribution for the normal metal. This distribution describes the temperature of the electron system in the normal metal. This temperature in turn is proportional to the power absorbed in the normal metal. To simplify the model, it is usually assumed that the superconducting electrodes are thermalised to the bath temperature, yielding \( f_N(E) = f_S(E) \). This assumption is generally true if very high efficiency quasiparticle traps are used. However, in the case of the CEB, the currently used nanofabrication process prevents the fabrication of such normal metal traps. Agulo et al. [29] demonstrate the use of such traps in case of an electron microrefrigerator and O’Neil [30] explores in detail the use of overlayer traps with a physical model describing it.

Figure 2.4: (a) Energy diagram of an unbiased NIS junction. (b) Energy diagram of a biased NIS junction.

**Power deposited in Normal Metal**

The following equations are written in such a way that every process that increases the electron temperature of the absorber is considered positive
while every cooling process is considered negative. This approach is similar to [30, and references within], and is opposite to that in [31]. For instance, negating Eq. (2.5) is required to estimate the “cooling power” of a NIS junction. This difference in sign propagates through to the heat balance Eq. (2.8) where absorbed electromagnetic power $P_0$ is considered positive and the power lost from the electron system to the phonon system $\Sigma \Lambda (T_e^5 - T_{ph}^5)$ is considered negative. Both approaches are equivalent.

The tunnelling electrons in the NIS junction carry some energy (power); this power can be calculated by removing one $e$ in Eq. (2.4) and replacing it with $eV - E$ which is the energy deposited in the normal metal from one tunnelling event. Doing this we obtain [30]

$$P_N = \frac{1}{e^2 R_N} \int_{-\infty}^{\infty} (eV - E) \nu(E) (f_N(eV - E) - f_S(E)) dE. \quad (2.5)$$

**Power deposited in Superconducting Electrode**

Similarly, the tunnelling current carries energy (power) into the superconducting electrode. This power, abbreviated $P_S$, can be calculated from energy conservation

$$P_S = IV - P_N \quad (2.6)$$

$$P_S = \frac{1}{e^2 R_N} \int_{-\infty}^{\infty} E \nu(E) (f_N(eV - E) - f_S(E)) dE. \quad (2.7)$$

In a superconductor, the tunnelling electrons from the normal metal side create excitations (quasiparticles) at or above the gap energy. If the NIS junction is biased near the gap (for maximum cooling), the average quasiparticle energy is equal to the gap energy ($\Delta$). In a typical superconductor like aluminium, quasiparticle recombination time is rather long (of the order of $\mu$s) [32, 33, 34], and the only efficient way to remove these excitations is the use of normal metal traps. These traps can take the form of lateral traps, overlayer traps or underlayer unbiased NIS junction traps. In the current fabrication scheme of the CEB, the only possible traps are the underlayer unbiased NIS traps due to the fact that the normal metal absorber is evaporated and oxidised before the deposition of superconducting electrodes. The efficiency of underlayer NIS traps is poor (proportional
to barrier transparency). It is possible to create overlayer metal traps in the CEB by evaporating a normal metal on top of the superconducting electrode but this decreases the $T_c$ of the electrode with many undesirable side effects (e.g., reduced energy gap at the temperature of operation).

**The $\beta$ parameter**

The $\beta$ parameter was introduced by Fischer et. al [35]. Essentially, $\beta$ is the fraction of power returning from the superconductor to the normal metal absorber. This “reheats” the absorber, decreases the cooling efficiency of the tunnel junction and decreases the responsivity of the device. The magnitude of this returning power is $\beta P_S$.

Assuming that all quasiparticles created in the superconducting electrodes due to the tunnelling current are at the gap energy ($\Delta$), the total energy deposited in the superconductor is $\frac{L_e}{e}\Delta$. In [29, 36], the magnitude of the returning power is described in the heat balance equation as $\beta\frac{L_e}{e}\Delta$. While this is a valid approximation, the current work uses the full integral calculation using $\beta P_S$.

**2.4.2 Heat balance equation**

To analyse the full structure of the CEB with two NIS tunnel junctions, a thermo-electric “heat balance” equation can be written that takes into account the energies associated with the heating processes (RF heating due to the signal and DC heating due to the bias current) and the cooling processes (electron cooling due to biased NIS tunnelling and electron-phonon interactions)

$$2P_N + 2\beta P_S - \Sigma\Lambda (T_e^{5} - T_{ph}^{5}) + I^2 R_a + P_0 + \delta P = 0. \quad (2.8)$$

Here, $P_N$ is the power transferred by the bias current, $P_S$ is the power deposited in the superconducting electrode, and $\Sigma\Lambda (T_e^{5} - T_{ph}^{5})$ is the heat flow from electron to phonon subsystems in the absorber where $\Sigma$ is the electron-phonon coupling constant which is material and temperature dependent, $\Lambda$ is the volume of the normal absorber, $T_e$ is the electron temperature of the absorber, and $T_{ph}$ is the bath temperature. $I$ is the bias current, $R_a$ is the resistance of the absorber, $P_0$ is the background power on the CEB in steady state (absorbed power), while $\delta P$ is the incident signal power.
2.4.3 Responsivity

Responsivity of the CEB is a change in the measured electrical parameter (voltage or current) per unit absorbed power. The absorbed power increases the temperature of the electron system and the tunnelling current decreases it via electron cooling. The distribution of electrons in the normal metal affects the current through the NIS junction. One can calculate the effect each heating or cooling process has on the electron temperature. At constant voltage, $\frac{\delta I}{\delta T_e}$ describes the current change through the device as a function of electron temperature. Similarly, the voltage change at constant current is $\frac{\delta V}{\delta T_e}$. The dependence of electron temperature on power is $\frac{\delta P}{\delta T_e}$ where $P$ describes the power transferred through the tunnel junction and $P_0$ describes the absorbed signal power. The responsivity is the ratio

\[ S_I = \frac{\frac{\delta I}{\delta T_e}}{\frac{\delta P}{\delta T_e}} = \frac{\delta I}{\delta P_0} \]  

(2.9)

\[ S_V = \frac{\frac{\delta V}{\delta T_e}}{\frac{\delta P}{\delta T_e}} = \frac{\delta V}{\delta P_0}. \]  

(2.10)

The full expressions of the responsivities are shown in Eq. (2.11) and Eq. (2.12). The denominators of these equations describe the thermal conductance of the electron-phonon and the NIS heat exchange channel. The change in electron temperature $\delta T$ connects the changes in absorbed power $\delta P$, current $\delta I$ and voltage $\delta V$. The factor $5\Sigma\Lambda T_e^4$ represents the thermal conductance between the electron and phonon systems while the second term in denominators of Eq. (2.11) and Eq. (2.12) represents the thermal conductance ($\frac{\delta P}{\delta T}$) of the NIS junctions. The current and voltage responsivities are plotted in Fig. 2.5

\[ S_V = -2\frac{\frac{\delta I}{\delta T}/\frac{\delta I}{\delta V}}{5\Sigma\Lambda T_e^4 + 2\frac{\delta P}{\delta T} - \frac{\delta I}{\delta T}/\frac{\delta I}{\delta V} \cdot \frac{\delta P}{\delta V}} \]  

(2.11)

\[ S_I = 2\frac{\frac{\delta I}{\delta T}}{5\Sigma\Lambda T_e^4 + 2\frac{\delta P}{\delta T}}. \]  

(2.12)


Figure 2.5: Current and voltage responsivities plotted using Eq. (2.12) and Eq. (2.11). This plot has been calculated for $R_N = 1 \text{k}\Omega$, $P_0 = 0.5 \text{ pW}$, $\Lambda = 0.023 \text{ \mu m}^3$, $\Sigma = 1.5 \frac{nW}{\text{nm}^2 K}$, $\beta = 0.03$ and $T_{ph} = 0.3 \text{ K}$. Note that the absolute value of $S_V$ is plotted for the sake of comparison.

2.4.4 Noise and Noise Equivalent Power (NEP)

There are three components of the noise in a CEB based system, the noise due to electron-phonon interactions, the noise due to the NIS tunnelling, and the noise due to readout amplifiers. The electron-phonon noise is described as [37]

$$NEP_{e-ph}^2 = 10k_B \Sigma \Lambda(T_e^6 + T_{ph}^6).$$  \hspace{1cm} (2.13)

The noise due to the tunnelling through the NIS junction has three components. The first component is due to the discrete nature of tunnelling charges, called the shot noise $(2eI/S_v^2)$. The second component is noise due to thermodynamic fluctuations of the heat flow through the tunnel junction since the tunnelling current also removes the hottest electrons from the absorber and cools the electron system with each tunnelling event. The third component is the correlation between the two processes [31]. The NEP of a NIS junction in current biased mode is
2.4. The Cold-Electron Bolometer model

Figure 2.6: Simulation of NEP using Eq. (2.18). This plot has been calculated for \( R_N = 1 \, \text{k}\Omega, P_0 = 0.5 \, \text{pW}, \Lambda = 0.023 \, \mu\text{m}^3, \Sigma = 1.5 \frac{nW}{\mu\text{m}^3 K^5}, \beta = 0.03, V_n = 3 \frac{nV}{\sqrt{\text{Hz}}}, I_n = 3 \frac{fA}{\sqrt{\text{Hz}}} \) and \( T_{ph} = 0.3 \, \text{K}. \)

\[ \text{NEP}_{\text{SN}}^2 = \frac{\langle \delta I^2 \rangle}{S_I^2} - 2 \frac{\langle \delta P \delta I \rangle}{S_I S_V} + \langle \delta P^2 \rangle. \] (2.14)

It should be noted that the responsivity in current biased mode \((S_V)\) is negative and the factor 2 in the middle term is an internal correlation factor. Thus the correlation term in Eq. (2.14) is positive and adds to the total NEP. In the case of voltage biased mode, the responsivity \((S_I)\) is positive and hence the NEP decreases. The NEP of a NIS junction in voltage biased mode is

\[ \text{NEP}_{\text{NIS}}^2 = \frac{\langle \delta I^2 \rangle}{S_I^2} - 2 \frac{\langle \delta P \delta I \rangle}{S_I} + \langle \delta P^2 \rangle. \] (2.15)

The amplifier noise consists of the voltage and current noise spectral densities \((V_n \text{ and } I_n \text{ respectively})\). The current noise of any commercial JFET amplifier can be estimated from its input bias current \((I_b)\) where \( I_n = \sqrt{2eI_b} \). If cold JFETs are used (cooled to 110 K), then the current and voltage noise are lower than the values reported in the datasheet and need to be measured \([38]\).
into account. On the other hand, the voltage biased CEB could be read out by SQUID amplifiers, where the current noise dominates. In the calculation of NEP due to amplifiers, the respective noise components are scaled with responsivity to convert them to equivalent power values

\[
NEP_{\text{amp}}^2 = \frac{V_n^2 + (I_n \frac{2\delta V}{\delta I} + R_a)^2}{(S_V)^2} .
\]  

In case of voltage biased mode with SQUID readout, the dominant noise contribution is the SQUID current noise \( I_n \). The voltage noise can be disregarded and the NEP can be written as

\[
NEP_{\text{amp}}^2 = \frac{I_n^2}{S_I^2} .
\]  

The total NEP is the sum of individual NEP contributions (Fig. 2.6)

\[
NEP_{\text{total}}^2 = NEP_{NIS}^2 + NEP_{e-ph}^2 + NEP_{\text{amp}}^2 .
\]  

2.4.5 Effect of quasiparticles in the superconducting electrode

The creation of quasiparticles in the superconducting electrode due to the bias current brings some undesirable effects in the NIS performance [39]. The early CEB model relies on the idea that all quasiparticles created in the superconducting electrode due to tunnelling current are thermalised to bath temperature \( T_{qp} = T_{ph} \), but it is not realistic, especially in a CEB where QP traps do not exist.

The quasiparticle heating of a superconducting volume is well known, and its impact is felt on the electron-phonon coupling due to a very strong pre-factor [40] of \( 0.98 e^{\frac{-\Delta}{k_B T_{qp}}} \), where \( T_{qp} \) is the quasiparticle temperature, and \( \Delta \) is the superconducting gap. To find the temperature of quasiparticles, we can set up and solve a heat balance equation in the superconducting electrodes similar to the normal absorber as shown in Eq. (2.19). Here, \( \Sigma_S \) is the electron-phonon coupling constant of the superconductor, and \( \Lambda_S \) is the volume of the superconducting electrode. The two heat balance equations (Eq. (2.8) and Eq. (2.19)) are solved in a self consistent manner to evaluate \( T_e \) and \( T_{qp} \)

\[
(1 - \beta)P_S - 0.98 e^{\frac{-\Delta}{k_B T_{qp}}} \Sigma_S \Lambda_S (T_{qp}^5 - T_{ph}^5) = 0 .
\]  

(2.19)
An example of the extracted values of $T_e$ and $T_{qp}$ are shown in Fig. 2.8. Electron cooling of the normal metal electrons system is clearly observed along with the increase in the temperature of quasiparticles in the superconducting electrode. The Fig. 2.7 shows the effect of quasiparticle overheating of the superconducting electrode on the responsivity of the CEB. Excess quasiparticles in the electrode cause a suppression of the responsivity leading to an increase in NEP of the device. We notice that electron cooling can be strongly suppressed leading to degradation of CEB performance.

In the model described above, an assumption is that the quasiparticles that tunnel from the normal metal to the superconductor are uniformly distributed in the superconducting electrode volume. In other cases (more realistic), there should be diffusion of quasiparticles from junction area to other areas of the electrode and QP-QP recombination setting up a thermal gradient. The author would like to note that the use of Eq. (2.19) is a simplification of the description of the nonequilibrium processes in the superconducting electrode but it is a reasonable approximation.

![Figure 2.7: Effect of quasiparticle heating in superconducting electrode on responsivity. The voltage responsivity is plotted in (a) and the current responsivity in (b). This plot has been calculated for $R_N = 1$ kΩ, $P_0 = 0.5$ pW, $\Lambda = 0.023$ µm$^3$, $\Sigma = 1.5 \frac{nW}{\mu m^3 K^5}$, $\beta = 0.03$ and $T_{ph} = 0.3$ K. The volume of the superconducting electrode $\Lambda_S = 300$ µm$^3$ has been chosen to clarify its effect on responsivity. $\Sigma_S = 0.3 \frac{nW}{\mu m^3 K^5}$.](image-url)
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2.5 Insensitivity to Cosmic rays

An important phenomenon that limits the sensitivity of bolometric detectors in space missions is the interaction of the bolometers with Cosmic rays, and the subsequent addition of this “noise” in the readout signal. This problem is well known [41, 42] and has been an important problem in recent space missions like Planck [43]. This factor will also determine the ultimate sensitivity of detectors in forthcoming missions like CORe [44], PRISM [45], etc. In several previous missions like BOOMERanG, large area spider-web bolometers were used [46, 47], which presented a large absorbing cross section to free space. The active area of the CEB (absorber+tunnel junctions) have a very small cross section (as low as a few µm²) and the device is expected to be largely immune to Cosmic ray hits.

In a study performed in 2014 [48], an array of 6 CEBs integrated in a cross slot antenna cooled to 304 mK was bombarded with high energy photons from the radionuclide $^{137}$Cs (Fig. 2.9). This source emits (85.1±0.2)% photons with energy of (661.657±0.003) keV. Given the geometry of the detector, the activity and distance of the source, and the intervening absorption, one event per 50 seconds should be observed (a spike in the voltage response) if the entire CEB chip (4 mm²) is sensitive.
Figure 2.9: (a) Schematic of the setup used to test the sensitivity of the CEB to high energy particles. (b) Experimental setup with an X-ray source illuminating the CEBs through the optical window of a cryostat.

to ionising radiation. The CEB array was current biased at its most sensitive point on the IV curve and data collected over 16 hours of irradiation of the CEB array showed no absorption event. The device was also irradiated with X-rays from a Microfocus X-ray source (model L10101 from Hamamatsu) in the range (10-100) keV producing a much higher flux than the radioactive source. For a large X-ray photon flux and high energy (large accelerating voltage), the detector signal developed an offset which was explained by a rise in the bath temperature of the cryostat cold stage. No noticeable increase in noise was observed, leading to a conclusion that due to the small absorber cross section of the device, CEBs are largely immune to high energy ionising radiation. The author believes that more experiments need to be performed, especially on distributed absorber CEBs to better understand the interactions of CEBs with high energy radiation.

2.6 Cold-Electron Bolometer arrays

The decoupling of the electron and phonon systems and small volume of the absorber plays a very critical role in determining the high sensitivity of the CEB. A given volume of absorber can handle a certain amount of power before the electron system is overheated and the responsivity decreases. To handle higher power loads on a pixel (in pW), a simple solution is
to increase the volume of the absorber proportionally. This approach is feasible up to a point where the cooling power of the NIS junctions is comparable to the absorbed RF power. Beyond this value the absorber will overheat, reducing the sensitivity. Decreasing the tunnelling resistance of NIS junctions to increase cooling power (via larger tunnelling current) is also feasible up to a certain lower limit set by the nanofabrication; low ohmic junctions can be leaky and dissipative. Large power loads typical of balloon-borne telescopes necessitate an array of CEBs to handle these levels of power. This creates a problem of efficiently coupling incident radiation equally to one (or many) detectors in the array in a way to avoid the overheating. Also, the balloon-borne experiments like OLIMPO have been designed to use cold JFET amplifiers as readout, since they are simple and been proven to work [49, 47, 50]. If an array of CEBs is used together with such a readout, it needs to be matched to its noise impedance. A solution was proposed to solve this problem: the parallel/series array of CEB detectors [51].

Let us assume a combination of $M$ CEBs connected in series and $W$ CEBs connected in parallel ($M \gg W$). The array is usually current biased due to high series resistance. The heatbalance equation for a single CEB can be modified as shown in Eq. (2.20). We assume that power is equally distributed among all the bolometers and solve the heatbalance for a single CEB in the array. The heatbalance equation for the normal metal is solved together with the heatbalance equation for the superconductor (Eq. (2.19)) as described earlier.

$$2P_N + 2\beta P_S - \Sigma A (T_e^5 - T_{ph}^5) + I^2 R_a + \frac{P_0 + \delta P}{M \times W} = 0 \quad (2.20)$$

The voltage responsivity will be divided by $W$. The impact of the current noise of the amplifier $I_n$ will be felt across the differential resistance of the array $\frac{2\delta V M}{\delta I W}$

$$NEP_{amp}^2 = \frac{V_n^2 + I_n^2 \left( \frac{M}{W} \left( \frac{2\delta V}{\delta I} + R_a \right) \right)^2}{\left( \frac{S_V}{W} \right)^2} \quad (2.21)$$

The NEP of the NIS junction can be calculated from Eq. (2.14). The total NEP is the sum of individual NEP contributions scaled with $M$ and $W$. Thus we can see that an array of $N$ bolometers increases the noise by $\sqrt{M}$ but can absorb $M$ time the power. This fact is useful in the case of balloon-borne telescope missions where the power loads from atmosphere...
are very high but the number of bolometers in one pixel have to be limited for photon noise limited performance

\[
NEP_{total}^2 = M \times W \times NEP_{NIS}^2 + M \times W \times NEP_{e-ph}^2 + NEP_{amp}^2.
\]  

(2.22)

A parallel array of CEBs is a low impedance distributed-absorber where \( M << W \). While the series connected CEBs have impedances that are matched to JFET amplifiers, it is currently not possible to multiplex these systems to form large imaging arrays containing 1000s of pixels. On the other hand, SQUID based readout systems have been successfully multiplexed to create large arrays of TES, e.g. [52]. The SQUID input impedance is usually of the order of 1 \( \Omega \) and the detector impedance needs to be matched to this value. In the case of CEB detector, the NIS nonlinearity is inherently high ohmic. The maximum current responsivity occurs at a voltage bias corresponding to \( 0.9 \Delta e \) where \( \Delta e \) is the differential resistance is the lowest. Assuming that the normal metal absorber has a finite resistance at the temperature of operation, and the normal state resistance of a NIS junction of a reasonable size (~1 \( \mu m^2 \)) is about 50 \( \Omega \), the operating point impedance of a single voltage biased CEB approaches 100 \( \Omega \) (due to 2 NIS junctions in series).

A simple way of decreasing CEB impedance is to connect them in parallel. To integrate this parallel circuit in a traditional slot antenna is difficult primarily due to size restrictions but also due to the fact that the antenna impedance can be much larger than that of the parallel circuit. The FSS based distributed architecture offers an interesting solution to this problem. The FSS elements could be connected in parallel for DC bias while being simulated together with the DC lines for proper RF coupling. One such device was fabricated and measurements are reported in Section 4.4.

The parallel CEB array can be thought in similar terms as the series array albeit with a voltage bias due to low impedance. The contribution of amplifier NEP to the total NEP is lower than the current biased case. The impedance matching to SQUID input impedance (1 \( \Omega \)) can be done with a superconducting transformer.

In a recent development, the capacitance of the NIS junction of the CEB has been proposed to be used with the kinetic inductance of a narrow superconducting line of niobium nitride creating a resonator [53]. This resonator could be implemented in a broadband antenna and could selectively couple power from a designed band of frequencies.
2.7 Data analysis

There are two ways of analysing the bolometer data depending on the amount of power absorbed in the device. For large power loads the IV curve of device can be fitted to the CEB model and the absorbed power can be estimated. For a small variation of signal power $\delta P$ on top of a larger static power load like atmospheric background $P_0$, one can compute the responsivity at that power load using Eq. (2.11) or Eq. (2.12), and estimate the signal power using Eq. (2.9) or Eq. (2.10). This approach is only feasible if the signal power is much smaller than the static background power load since it does not change the electron temperature in the absorber to any appreciable extent.

![Figure 2.10: (a) Measured IV curve of the 145 GHz test pixel along with the fit and extracted value of responsivity. (b) Differential resistance (circles) and the fit (solid line) corresponding to the same sample.](image)

Typically, the laboratory raw data are series of Current-Voltage (IV) curves in dependence on power incident from a blackbody radiation source. These calibration curves can be fit to the CEB model by solving Eq. (2.20) and comparing the modelled IV curve with experiment as shown in Fig. 2.10(a,b). This is easily achieved by use of a numerical package such as Matlab where one can fit the experimental curve to the model by multivariable regression.

The speed of fitting can be improved by introducing previously measured values of variables ($T_{ph}, R_N, R_a, \Delta, V_n, I_n$). The program then needs to find suitable values for the “unknowns” - $\gamma, \beta$ and $P_0$. These are dependent on actual conditions during the experiment or dependent on
fabrication. For a given device, all variables except $\gamma$ and $P_0$ remain unchanged. The parameter $\gamma$ is dependent on the experimental environment while $P_0$ changes depending on magnitude of the incident power. Using the fitted values of these variables, the value of responsivity can be estimated. Laboratory experiments can be represented as response curves shown in Fig. 2.11. These are created by subtracting an IV curve measured at a given temperatures of the blackbody from a curve taken at the lowest temperature of the radiator 2.6 K. Estimating the responsivity at a blackbody temperature of 2.6 K, one can estimate absorbed power at various radiation temperatures by fitting the responsivity curve with the response curves.

![Figure 2.11](image.png)

Figure 2.11: Fitting the optical response of a 345 GHz test pixel (O2-12) using Eq. (2.20). The solid line shows the data fit to the CEB model.

Using this approach, a map of the CEB responsivity to incident power can be prepared in the laboratory. For an actual experiment like OLIMPO, a lookup table can be prepared which will allow to pick up a value of responsivity depending on the current background load. This changing background creates a large change in the readout voltage at a given bias current and this offset from a pre decided “dark” IV curve can be used to pick the right value of responsivity at that background power. This is important since different power levels can call for biasing the device at different bias points for lowest NEP. On the OLIMPO focal plane wafer, we have a SINIS thermometer that can be used to track the bath temperature $T_{ph}$. To map the change of bath temperature to responsivity, one can measure IV curves at various power loads at various bath temperatures and create a 3 dimensional map of the responsivity in dependence on
these parameters. In OLIMPO, the integration time for multiple passes over a target can be of the order of 10 minutes and we assume that the background power load $P_0$ will remain constant over this period of time.

2.8 Summary

This chapter has provided a short introduction to superconductivity, NIS tunnelling and the various aspects of the CEB operation. Previously published model of the CEB has been introduced together with explanations of the key parameters like responsivity and sources of noise in the bolometer. A short amendment is made to the model by introducing a method to calculate the heating of the electron system in the superconducting electrode of the CEB. The effect of this heating is seen in the suppression of responsivity. The new model is a better representation of CEB operation and it has enabled us to fit measured optical response data for the first time. A short account is given of the experiments to test the sensitivity of the CEB to high energy particles by bombarding it with radiation from a radioactive source and a X-ray source. The seeming absence of the bolometer response to this energetic radiation is a positive step towards making a bolometric focal plane array which is insensitive to Cosmic rays. Arrays of CEB are described in this chapter and the already published model can be used to design a distributed absorber bolometric system. Such a design has the ability to cover a large physical area on the telescope focal plane and distribute the absorbed signal power over a large number of detectors to reduce overheating and improve responsivity. Finally, a brief account of data analysis is presented at the end of the chapter.
Frequency Selective Surface based detectors

Frequency Selective Surface (FSS) is a periodic arrangement of simple metallic repeating patterns that interact with incident electromagnetic radiation. The FSS acts as a reactive element in the path of a propagating electromagnetic wave. It can transmit, reflect or absorb radiation in a band of frequencies. This “metallic mesh” is popular in millimeter and sub-millimeter wave optics as a lowpass, highpass, bandpass and notch filters. Metallic mesh half wave plates have been designed to replace birefringent crystal based half wave plates over a broad bandwidth with low losses [54]. FSS have military application in reducing the radar cross section of antennas on aircraft. In short, the FSS has become an indispensable element in modern electromagnetics.

In microwave circuit analogy, an FSS element has an inductance with mutual capacitance between neighbouring elements. The simplest element is a metallic wire. A long wire can be represented as an inductance while short length of wire separated by small gaps can be represented as a series circuit of an inductance and a capacitance [55, 56]. At the resonance frequency, such an array of short wires acts as a perfect reflector. Conversely, if the short wires are replaced by similarly shaped gaps in a ground plane, being on resonance enables complete transmission of the appropriate wavelength. The bandwidth of such arrays can be modified either by increasing the inter-elemental distance or by changing the size of the element
while keeping the element pitch constant. Larger pitch produces narrower bandwidth. The bandwidth is also modified in the presence of a dielectric slab which is usually present for mechanical support. Wider wires produce wider bandwidth by lowering the inductance and thus the quality factor of the resonator (for the same inter element spacing). Some elemental shapes have an inherent bandwidth larger than others; loop shapes in general exhibit wider bandwidth. Loop shapes are also convenient for integrating two terminal bolometers in. A thorough discussion of FSS is provided in [56].

Most FSS based transmission filters and gratings are designed to provide a lossless interaction with frequencies of interest. Lossy FSS grids can be designed by loading the FSS element with a resistance. Controlling this resistance controls the damping of the resonance of the FSS (lowering the quality factor). Thus a FSS grid can be designed to be lossy at specific frequencies. This was the approach used in Frequency Selective Bolometers (FSB) which was the earliest attempt at integrating a bolometer with a resonant grid [57] (and a broader discussion in [58]). The resonant interaction of radiation with the lossy FSS produced heating of a silicon nitride membrane suspended by thin legs with low thermal conductance to the supporting structure. The heating is measured with a Transition Edge Sensor. Compared to traditional spider-web Transition Edge Bolometers which requires external quasioptical filters to define the bandwidth, the FSB is advantageous because it defines its own bandwidth and measures power in this band.

The earliest attempt at a distributed detector array with the Cold-Electron Bolometer was a dipole array proposed in 2008 [59]. These were incoherent dipole arrays based on a distributed antenna-coupled absorber concept first described in [60, 61, 62]. These devices were either single or dual polarised or unpolarised absorbers coupled to half wave dipoles. The main advancement was a distribution of the incident power over a large number of individual bolometers to reduce overheating of each one and match the impedance of this array to a high impedance JFET readout. To cover an area the size of the diffraction spot on the focal plane (few mm$^2$), this design required a large number of unit cells (with bolometers) which increased the total impedance and worsened the noise matching.

The next attempt with integration of CEBs with metallic mesh type bandpass structures (similar to Fig. 3.1) was reported in 2014 and is discussed in this chapter. This design is based on a traditional FSS with lossy loop shaped elements. The lossy component is actually the CEB absorber which heats up as a result of high frequency currents excited on the loop.
3.1 Optical modelling

One Dimensional Model

An FSS can be analysed in the framework of a traditional transmission line. This technique was developed by Ulrich and described in [55, 63]. Essentially, any array of metallic elements (wires, loops, closed shapes,...) can be described as a shunt to a transmission line. A simple one dimen-

Figure 3.1: (a) HFSS model of a unit cell of a Frequency Selective Surface. The bright metallic square element has four bolometers embedded in its sides. Radiation is incident from the side of the Silicon substrate (shaded dark) and backed by a backshort (top plane). The scale bar is 660 µm and the length of each side of the unit cell is 500 µm. (b) A schematic of bolometers embedded in the FSS element. The size of each arm of the element is 200 µm × 15 µm. Connecting lines allow DC connections to neighbouring elements.

The response of the array of CEBs is treated in the same way as in [59]. The current design has all the characteristics of a FSS - scalability, large coupling in the resonance band and narrow bandwidth. The FSS is fabricated on a Silicon substrate of reasonable thickness (>100 µm) and is structurally very robust. The Silicon thickness is also a tuning parameter. An account of measurement of these kinds of devices is given in Chapter 4.

This chapter describes the optical modelling of FSS based CEB distributed absorber. A design strategy is outlined in Section 3.1. Section 3.2 and Section 3.3 describe particular examples of FSS based CEB arrays that have been designed for OLIMPO and LSPE balloon-borne telescopes.
sional transmission line equivalent circuit diagram is shown in Fig. 3.2. The FSS layer with integrated bolometers serves as an absorber with impedance matching to the incident electromagnetic radiation together with the substrate and the backshort. The impedance of the substrate is modelled as a transmission line with a finite electrical length corresponding to its thickness in series with the free space impedance of 377 Ω. Similarly, a transmission line equivalent for the backshort is calculated depending on the backshort distance from the FSS. These two impedances are arranged in parallel to the FSS impedance. At resonance, the imaginary part of the FSS surface impedance is tuned out by the substrate and the backshort impedances. Since high frequency currents are excited in the FSS motif, they pass through the matched load (CEB) present in the arms of the motif, cause dissipation of power in the CEB and create a voltage/current response which can then be read out.

![Diagram of one dimensional transmission line model](image_url)

Figure 3.2: One dimensional transmission line model of a measured sample. Impedances corresponding to transmission line equivalents of the substrate, FSS and the backshort are shown. The wavelength (λ) corresponds to the wavelength in the material (Silicon or vacuum). The impedance of backshort, substrate and the FSS are labelled with $Z_{BSH}$, $Z_{SUB}$, and $Z_{FSS}$ respectively. The dotted lines show the equivalent circuit of the backshort and substrate.

Using the one dimensional model described above, an estimate can be made of the impedance offered by the substrate and the backshort.
Initially, a suitable guess is made of the thickness of the substrate and a suitable backshort distance and their impedances are calculated using the transmission line equation.

The transmission line equivalent that corresponds to the backshort length can be considered to be lossless and its impedance $Z_{BSH}$ is

$$Z_{BSH} = 377 \times i \tan(k_{BSH} \times H_{BSH}).$$  \hspace{1cm} (3.1)

Here, $k_{BSH}$ is the wave number in vacuum and $H_{BSH}$ is the distance to the backshort. The series combination of the substrate with the wave impedance in vacuum $377 \, \Omega$ gives an equivalent substrate impedance $Z_{SUB}$

$$Z_{SUB} = Z_0 \times \frac{377 + Z_0 \times i \tan(k_{SUB} \times H_{SUB})}{Z_0 + 377 \times i \tan(k_{SUB} \times H_{SUB})}.$$  \hspace{1cm} (3.2)

Here $k_{SUB}$ and $H_{SUB}$ are the wave number in the substrate and the substrate thickness. Similarly, the impedance offered by the combination of substrate and free space is calculated as

$$Z_0 = \frac{377}{\sqrt{11.7}}.$$  \hspace{1cm} (3.3)

The wave impedance in vacuum is taken to be $377 \, \Omega$ and the relative permittivity of Silicon is assumed to be 11.7 in Eq. (3.3). The value of $Z_0$ will be lower for silicon substrate which has been thinned to the required thickness (~100 µm) for the resonance of the FSS and Eq. (3.3) is just an approximation.

**Impedance**

The impedances are plotted in Fig. 3.3(a) for a thickness of Silicon of 140 µm and distance to the backshort of 160 µm. The imaginary part of the impedance of the substrate is capacitive and dominates that of the backshort. Fig. 3.3(b) shows the impedance of the FSS. This can be estimated from simulations by moving the reference plane to the FSS surface thus de-embedding the substrate out. Alternately, one can de-embed the substrate out by removing the parallel substrate impedance component calculated using the transmission line model. The simulations need to be done with the FSS illuminated together with the substrate since the calculation then includes the effect of the near fields excited in the substrate. In this region, the transmission line model of the substrate impedance is not strictly valid but it remains a reasonable approximation.
Figure 3.3: (a) Substrate and backshort impedance. (b) Impedance of the FSS computed using two orthogonal modes of the Floquet excitation. The difference is due to the presence of connection lines in one direction (x) that increases the inductive part of the impedance.

Scaling up the size of a FSS causes a shift in the resonance frequency. An equal scaling in all three dimensions causes the resonance frequency to be shifted inversely proportional to the scaling factor. FSS based devices are fabricated using photo- or electron beam lithography with resolution and alignment accuracy better than 1 µm. The most critical element is the etched Silicon substrate. In the absence of Silicon wafers of the required thickness, Silicon can be wet or dry etched. The accuracy of the etch stop depends upon accurate knowledge of the initial thickness of the wafer and the process etch rate. The wafer thickness can be measured in a variety of ways but the optical surface profiler is recommended. The etch rate can be measured using a stylus based surface profiler by removing the wafer from the etch process from time to time. Fig. 3.4 shows simulation of effect of thickness of Silicon on the FSS; a few µm can change the centre frequency of the device.

3.2 OLIIMPO detector design

DC design

The DC design for the planar array follows from [59]. Depending on the number of unit cells required to effectively cover the pixel area under the cold stop (described on p. 36), the bolometers can be connected in
Figure 3.4: Dependence of resonance frequency on the thickness of Silicon substrate as noted in the legend.

series/parallel to match the noise impedance of the cold JFET amplifiers. In the current design, the cold stop limits the area of the pixel to a circle with a diameter of 3 mm where 21 unit cells of the annular shape can be fitted, each containing 4 bolometers, giving a total of 84 bolometers. The performance of the array can be simulated by modelling the performance of 1 CEB and scaling the responsivity to $M$ CEBs each experiencing $M$ times less incident power. This analysis can be done using the heat balance equation that equates power incoming into the normal metal absorber of the CEB and the power leaving the absorber due to bias current at quasi steady state (Eq. (2.20)).

The most optimized combination of these bolometers taking into account the geometry and lowest possible NEP over the full range of incident powers (20 pW to 80 pW for OLIMPO estimations) is 42 bolometers in series and 2 in parallel. This corresponds to 21 unit cells of the FSS.

The NEP plots for two different power loads calculated from equations are shown in Fig. 3.5. We notice from the plots that the pixel with $42 \times 2$ bolometers performs well with NEP of the device less than the photon noise over a range of powers from 20 pW to 80 pW. Thus, the same pixel can be used for both the photometric and spectrometric configurations. The background power in the spectrometer configuration is a lot larger owing to emissions of uncooled spectrometer mirrors.

The unit cell of the OLIMPO focal plane pixel is an annular metallic shape with extended lines on all 4 sides. One opposite pair of lines
Chapter 3. Frequency Selective Surface based detectors

Figure 3.5: (a) DC simulation of OLIMPO 345 GHz pixel. (b) DC simulation of OLIMPO 480 GHz pixel. Both plots have been calculated for $R_a = 150 \, \Omega$, $R_n = 1 \, \text{k}\Omega$, volume of absorber $\Lambda = 0.025 \, \mu\text{m}^3$, $\beta = 0.1$, $\Sigma = 1.5 \frac{nW}{\mu\text{m}^3 \text{K}^5}$, amplifier voltage noise $V_n = 3 \frac{nV}{\sqrt{\text{Hz}}}$ and current noise $I_n = 3 \frac{fA}{\sqrt{\text{Hz}}}$. The photon noise has been calculated using the approximation $\sqrt{(2 P_0 h f + 2 P_0^2 / \delta f)}$.

terminate at a short distance from the unit cell edge such that the other pair of lines can facilitate DC connections to neighbouring cells in only one direction (x or y). This pattern is designed to be fabricated in Gold on a Silicon substrate of calculated thickness with a backshort. A schematic of the unit cell drawn in HFSS software [64] is shown in Fig. 3.6.

The unit cell is illuminated from the Silicon side as in traditional lens antennas. The Floquet port is used since it can illuminate a infinite periodic array of unit cells with a plane wave. Two orthogonal modes of the Floquet port are used to illuminate the FSS to test its performance as a dual polarised detector. The FSS surface together with the substrate and backshort form a resonant interference filter that couples to submillimeter radiation, where the backshort and the substrate tune out the reactance of the FSS layer. The unit cell structure is shown in Fig. 3.6 with four integrated detectors in the arms of the annular element. This geometry is similar to Fig. 3.1(b). In the simulation model, we represent the four CEB detectors each by a lumped port with the typical detector impedance. The losses in the gold film are also taken into account. The return loss ($S_{11}$) plot is shown in Fig. 3.7 (a).

By varying the phase angle between the periodic boundaries, the direction of plane wave illumination can be swept from $-90^\circ$ to $+90^\circ$ in both
3.2. OLIMPO detector design

Figure 3.6: The unit cell of the FSS on the left and close up view of the annular mesh element. The dimensions of the unit cell are $500 \mu m \times 500 \mu m$. The outer radius of the ring is $300 \mu m$ and it is $17.5 \mu m$ wide.

Fig. 3.7(b) shows result of this simulation; the FSS is sensitive to radiation over a wide range of angles of incidence. This makes it a suitable “absorbing surface” similar to a matched absorber used in [65]. But contrary to the SCUBA-2 absorber, the FSS based device is sensitive to incident power only over a small frequency range eliminating the need for a special bandpass filter, though a lowpass filter should be used to reduce impact of infrared radiation.

Figure 3.7: (a) Plotting the return loss of the FSS unit cell for two orthogonal modes of the Floquet port. (b) Angle dependent absorption of the FSS calculated for the two orthogonal modes ($\phi = 0^\circ$ and $\phi = 90^\circ$).
Chapter 3. Frequency Selective Surface based detectors

Figure 3.8: Model in HFSS of the lower part of the cold stop with CEB integrated FSS is shown on the left. Model of the upper part of the cold stop (horn) is shown on the right. The combined length is 20 mm.

Back-to-back horn based cold stop

Since the FSS is sensitive to radiation over a large solid angle, any power radiated from warm surfaces of the OLIMPO cryostat could potentially impact the pixel performance. Due to thermal budget restrictions, a cold stop is not considered. Instead, a new design of an array of horn based cold apertures was developed to limit the angle of visibility of the pixel. This design is similar to the one used on Planck satellite’s HFI instrument [66]. These apertures are mounted on the 300mK stage of the cryostat atop the pixels. This aperture is shown in Fig. 3.8, and consists of two back to back horns connected together with a 2 mm long section of a circular waveguide of diameter 0.9 mm. This waveguide is slightly overmoded with 5 modes at 345 GHz and 10 modes at 480 GHz. The top part of the cold stop was simulated as a traditional horn in the commercial package HFSS. The bottom part of the cold stop was simulated by exciting all possible waveguide modes in the central waveguide section and propagating the power in the direction of the FSS pixel. The return loss ($S_{11}$) for each mode excited in the waveguide is a good indicator of the optical coupling of the pixel.

The simulations of the top part of the cold stop indicate that it can illuminate the telescope optics reasonably well with an on-axis directivity of 23.4 dB and half power beam width of 17°. This directivity pattern is shown in Fig. 3.9(a,Top). The simulation of the bottom part of the cold stop...
3.2. OLIMPO detector design

stop with the FSS also shows promising results. For the full pixel of size ca. \(3 \text{ mm} \times 3 \text{ mm}\), the optical coupling is better than 50\% over the whole band. These results are shown in Fig. 3.9(a,Bottom).

![Figure 3.9](image)

**Figure 3.9:** (a)(Top) Simulated directivity of the horn facing the telescope optics. (Bottom) Simulation of the optical coupling of the 345 GHz single pixel with cold stop. (b) Simulation of optical coupling of the 480 GHz single pixel for the first 7 modes of the central waveguide.

The design of the 480 GHz pixel is similar to the 345 GHz design. The unit cell is similar to the one shown in Fig. 3.6 and is \(375 \mu\text{m} \times 375 \mu\text{m}\) in size. The thickness of the Silicon is 100 \(\mu\text{m}\) and the backshort is at a distance of 160 \(\mu\text{m}\). The size of the pixel is the same as the 345 GHz one since the arrangement of the pixels on the focal plane is the same for both the frequencies. Thus, this pixel can accommodate up to 49 unit cells \((7 \times 7)\). Simulations of the device noise and responsivity show that 37 unit cells (148 bolometers) are optimum and the pixel is fabricated according to these calculations.

The RF simulations of the pixel with the multimode horn are shown in Fig. 3.9(b). The coupling \((1-S_{11}^2)\) is plotted for the first 7 modes of the central waveguide. The coupling is better than 50\% over a bandwidth (-3 dB) of about 60 GHz. The fabricated focal plane array with 23 pixels and one thermometer is shown in Fig. A.3. The placement of the pixels is identical to the 345 GHz focal plane. The test pixels from this wafer are awaiting measurement as of the time of writing of this thesis.
Figure 3.10: (a) HFSS schematic of the 145 GHz pixel simulated with horn. The scale bar is 30 mm. The size of the pixel at the bottom of the horn is 6.5 mm × 6.5 mm. The size of the waveguide at the top is 5 mm while the part of the horn visible in the image is 37.5 mm long. (b) An overview of FSS designs for different frequency bands for LSPE.

3.3 145 GHz and 95 GHz prototype designs

The FSS design for the 145 GHz band is a scaling of the OLIMPO 345 GHz design. The scaled thickness of Silicon was 320 µm. Available commercial Silicon wafers had a thickness of 330 µm and the designed was tuned to this thickness to avoid Silicon etching. The FSS array constitutes 36 unit cells (6×6) and is series connected array of 72 CEBs (with 2 in parallel). This design is aimed towards the 145 GHz band on the SWIPE [67] instrument on LSPE balloon-borne telescope [11] but could also be used for similar instruments in future. The results of the LSPE multimode horn simulations have already been published in [68].

A full sized pixel was simulated in HFSS and the model is shown in Fig. 3.10(a) and measurements are described in Sec. 4.2. We use the same horn design and simulate the horn+FSS structure for the 220 GHz and 240 GHz bands. The results of these three designs are shown in Fig. 3.10(b). There is only a modest overlap between the 220 GHz and 240 GHz characteristics due to the narrow band nature of the design. These designs are being improved and will eventually be fabricated and characterised. We believe that the prototype designs described here can be a good solution for the far infrared polarimeter of the LSPE. Further information is found the LSPE web page [69].
A FSS design at 95 GHz is shown in Fig. 3.11. This design could have been scaled down from the 145 GHz one but the thickness of Silicon would be larger than 330 µm. Rather than trying to acquire the correct thickness of high resistivity Silicon wafers, the shape of FSS loop was modified for use with the available wafers. The outer diameter of the loop in Fig. 3.11(b) is 745 µm and the diameter of the inner circular hole is 123 µm. The size of the array consisting of 36 unit cells is 6.5 mm × 6.5 mm.

3.4 Summary

A general method has been introduced in this chapter to design FSS with integrated bolometric detectors. Along with high frequency simulations, a simple one dimensional model has been introduced as a quick way to get starting values for further in-depth numerical simulations. It has been shown that it is possible to design CEB based FSS arrays with the required pixel size and number of detectors to satisfy the mission requirements like NEP. A study of various CEB based designs show that it is possible to achieve bandwidths of up to 10% of the central frequency and coupling efficiencies approaching unity. Effects of various tuning parameters like substrate thickness on the optical coupling have also been studied.
OLIMPO is a balloon-borne reflective telescope with a 2.6 m mirror designed to image the sky in the mm and sub-mm bands [10, 70]. The OLIMPO detection bands have changed over the years according to the current scientific requirement, and today it has four diffraction-limited bolometric arrays centred at 145 GHz, 210 GHz, 345 GHz and 480 GHz. The detectors for the two lower frequency bands are the Transition Edge Sensor. The Cold-Electron Bolometer is a proposed detector for the 345 GHz and the 480 GHz band with 23 pixels on the focal plane [71, 72]. This chapter describes the low temperature characterisation of a single pixel for OLIMPO 345 GHz array along with design of mounting system in the OLIMPO cryostat. This test pixel (also called a “prototype” or a “sample”) was fabricated along with the focal plane and we expect its properties to match that of the focal plane devices. The pixel design, horn design and fabrication has been described in the preceding chapters. The measurement data from this chapter has been published in Paper 1.

4.1 345 GHz prototype characterisation

The simplest possible cryogenic measurement is the traditional hot/cold measurement where the sample’s optical response is tested to room tem-
Chapter 4. Characterisation of FSS based devices

Figure 4.1: (a) Scanning electron image of the 345 GHz test pixel showing the FSS elements. Each circular shape is 300 um in diameter. The scale bar is 200 um long. (b) Optical response of the sample to room temperature and liquid Nitrogen loading.

The sample is mounted on the 300 mK plate of the cryostat with the 345 GHz horn pointing to the open cryostat windows. The cryostat has three shields, the outermost shield at 300 K, the middle shield at 90 K and the innermost shield at 2.7 K. The outermost window is made of Teflon®. The middle window had a single layer home made Neutral Density Filter (NDF) (calibrated at 300 K only), and the innermost window had a similar NDF capped with Fluorogold.

The “hot” part of the hot/cold measurement involved illuminating the sample with radiation at 300 K from a blackened absorber, and an IV curve was recorded. The window was then covered with the black absorber dipped in liquid nitrogen at 77 K and another IV curve was recorded. The voltage response of the device is the difference between the two IV curves as shown in Fig. 4.1. The IV curves are plotted on the left axis. The estimated incident power was more than 550 pW at 300 K loading and more than 150 pW at liquid nitrogen loading. These values of incident power are much larger than the designed power load that the device can handle and reduce the responsivity of the device. The estimated responsivity after data fitting was $4.5 \times 10^6 \text{V W}^{-1}$.

Cold blackbody tests

To test the optical performance of the sample at lower power loads, a test setup was designed to fit inside the cryostat. The radiation source was a...
cold blackbody which was fabricated from a conical copper shape coated with a black mixture [73, and Ref. 29 within]. The mixture consisted of 68% Stycast 2850FT, 5% Catalyst 24LV, 7% fine carbon powder and 20% 175 µm diameter glass beads. The proportions were tried to be replicated as closely as possible.

The blackbody was heated with a 1 kΩ resistor and the temperature was measured with a Lakeshore® diode thermometer. The blackbody was mounted on the 2.7 K. stage of the cryostat with Teflon® spacer and screws to reduce heat leakage. The sample was mounted with the 345 GHz horn facing the blackbody such that the Blackbody completely illuminated the horn aperture. Lowpass and bandpass filters from QMC Instruments [74] provided the correct passband.

Fig. 4.2(a) shows the schematic of the experimental setup. The blackbody was heated with the heater and its temperature monitored continuously with a Neocera temperature controller. The heating of the blackbody beyond 6 K created thermal gradients in the cold stage and response measurements were limited up to this temperature. In one type of measurement, an IV curve was recorded at 2.6 K blackbody temperature and compared with IV curves recorded at 3.6 K and 4.5 K. The optical response and corresponding data fits are shown in Fig. 4.3(a). Estimates of responsivity and incident power are shown in Fig. 4.3(b). The reduction of responsivity is due to the increasing electron temperature of the CEB absorber. Rough estimations of optical efficiency can be made from these plots; an efficiency of 50% is indicated.
Chapter 4. Characterisation of FSS based devices

Figure 4.3: (a) Optical response at two different Blackbody temperatures. (b) Measured response and estimated responsivity and absorbed power on.

Spectral response

The most interesting optical characterisation of the single pixel is the frequency response. RF modelling described in Chapter 4 can be verified using an experimental setup described in Fig. 4.2(b). The submillimeter source is a Backward Wave Oscillator (BWO). The sample is placed on the 300 mK stage of the cryostat in the OLIMPO horn facing the optical windows. Band defining filters are excluded from this measurement apart from a low pass filter with cut-off greater than 700 GHz. The optical window on the 2.7 K stage is covered with two layers of Fluorogold and a NDF to attenuate microwave radiation. The 90 K window has a small 5 mm diameter aperture to avoid overheating of the cold stage. The outer window is made from Teflon®. The environment is covered with radiation absorbing foam to reduce multiple reflections.

The signal from the BWO is chopped at 21 Hz with a chopper positioned at 45° from of the optical window. A pyroelectric detector is used to measure the power output from the BWO. When the chopper covers the optical window it directs the BWO radiation at the pyroelectric detector. When the optical window is “open”, the BWO radiation passes inside the cryostat. The power output of the BWO is usually unstable; this method of using a pyroelectric detector allows us to get a semi-instantaneous estimate of incident power. In general we are not interested in the absolute value of incident power; we plot the voltage response of the FSS pixel against the response of the pyroelectric detector and normalise the ratio to the maximum to get an idea of the spectral response of the pixel. This is
Figure 4.4: (a) Frequency response of FSS based pixel measured with BWO at Rome University. FSS with square shaped elements were used in this test pixel. (b) Frequency response measured with a BWO at Chalmers University. The solid line shows simulations while the connected data points are measurements.

necessary since calibrated NDFs were not available during the course of this measurement. A relative response measurement is acceptable since the pyroelectric detector has a uniform response in the bandwidth of the BWO.

Apart from BWO measurements, an identical sample was measured at Rome University using similar equipment. The spectral response closely matches the one recorded at Chalmers University. The Fig. 4.4 shows the recorded spectral data at Rome University and Chalmers. The spectral response closely agrees with RF simulations and is a first proof of the frequency selective nature of the FSS architecture. In addition, spectral response was measured for FSS pixel with the square motif and the measurements agree with simulations. These details are published in Paper 1 and Paper 2.

NEP Estimation

Bolometer noise is an important parameter defining the performance of the device under test. From Chapter 3 we learn that several different physical processes in the CEB contribute to the internal noise of the device. In addition, the external component of noise is the amplifier noise. The OLIMPO detectors are designed to be matched to the noise impedance of cold JFET amplifiers. While the low noise individual amplifiers at Rome
Figure 4.5: Estimated NEP from noise measurements. The modelled device noise is 4-5 times lower than the measurements. The solid line over the NEP data is a guide for the eye.

University could not be replicated at Chalmers, we used commercially available JFET operational amplifier AD743 at room temperature instead to measure the noise performance. Unfortunately, the measured noise is dominated by pickup of common interferences like the power line frequency and noise from the room temperature current source. In addition, the pulse tube cryostat employed for measurements itself vibrates at 0.8 Hz making “low noise” operation impossible. The measurements shown in all attached papers are made with the pulse tube compressor shut off to reduce this very low frequency component. In addition, the cryostat wiring is traditional manganin unshielded twisted pair. Thus the measurements shown in Fig. 4.5 are made with the lowest possible noise configuration that could be achieved in the lab. It is completely dominated by interferences but it is still informative. The NEP is calculated from noise recorded as a function of device bias and divided by estimated responsivity of the device. The noise is recorded at 115 Hz with a lock in amplifier so that the measured noise is above the 1/f corner of the readout amplifier. The estimated NEP is about 4-5 times larger than the theoretically modelled NEP. We believe that improving the measurement setup similar to [75] is required to measure the true noise performance of the system.
Figure 4.6: (a) Schematic of the RF response measurement setup. (b) Optical image of the measurement setup mounted in the cryostat.

### 4.2 145 GHz prototype characterisation

The 145 GHz prototype is a FSS with a periodic ring shape which has 4 CEBs integrated in the ring. The sample is designed to fit the LSPE multimode horn. The optical response setup was the same as Fig. 4.6(a,b) with the smaller sized horn used for the 95 GHz tests due to insufficient space in the cryostat to mount the full sized horn. The optical response of the test pixel to blackbody radiation is shown in Fig. 4.7. The estimates of absorbed power from data analysis is also plotted on the right hand y-axis of the Fig. 4.7.

### 4.3 95 GHz prototype characterisation

**Cold Blackbody tests**

The optical response of the 95 GHz array was measured by radiating it with blackbody radiation from a cold blackbody source similar to Fig. 4.2(a). The LSPE horn described in [68] is too large to mount it in our cryostat together with the blackbody. A smaller version of this horn was prepared. The aperture of the horn was decreased to an opening of 5 mm in diameter to reduce background radiation. The blackbody was heated in a range of 2.7 K to 4.2 K and IV curves were recorded as a function of blackbody temperature. Using Eq. (2.20), we have fitted the measured IV character-
Figure 4.7: Measured optical response of the 145 GHz test pixel to black-body radiation. The estimation of absorbed power from data analysis is plotted on the right y-axis.

Figure 4.8: (a) The CAD Schematic of the 145 GHz prototype. The series array is connected between the top two contact pads while a thermometer is placed between the bottom contact pads. The size of the chip is 11 mm × 11 mm. (b) Optical image of the test pixel mounted on the horn.
4.3. 95 GHz prototype characterisation

Figure 4.9: (a) The CAD Schematic of the 95 GHz prototype. The series array is connected between the top two contact pads while a thermometer is placed between the bottom contact pads. Two columns of FSS elements are placed on either side of the main array as dummy elements for fabrication tests. The size of the chip is 11 mm × 11 mm. (b) Optical image of the test pixel mounted on the horn.

istics to the CEB model. These fits are shown in Fig. 4.10(a). The IV curves are scaled in current gain for clarity; the bias current at the point of maximum responsivity is 5 nA. Responsivity of the device estimated using data fitting is shown in Fig. 4.10(b) and it approaches $1 \times 10^8$ V/W for about 60 pW of absorbed power. Comparable values of responsivity are reported for metallic CEB in [76].

The estimated background power inside the cryostat was 47.2 pW. The value of absorbed power for each IV curve was extracted from the data fits and these power levels are shown in Fig. 4.11(a) after subtracting the background power on the device. The CEB array is designed to work with JFET amplifiers.

The voltage noise [38] from a JFET cooled to 120 K is about $4 \times 10^{-9}$ V Hz$^{-1/2}$. Using a cooled JFET amplifier as the first stage of the readout of this pixel can bring a readout limited NEP of $4 \times 10^{-17}$ W Hz$^{-1/2}$ for a background power load of 60 pW using the responsivity values from Fig. 4.10(b). The photon NEP ($\sqrt{(2P_0 hf + 2P_0^2/\delta f)}$) in this case is $5.6 \times 10^{-16}$ W Hz$^{-1/2}$. Here $h$ is the Planck constant, $f$ is the centre frequency (95 GHz) and $\delta f$ is the optical bandwidth. A more innovative
Figure 4.10: (a) Measured IV curves at blackbody temperatures 2.6 K, 3.13 K, 3.42 K, 3.74 K, and 4.12 K, from bottom to top. The corresponding data fits using Eq. (2.20) are also shown. The IV curves are scaled with a current gain for clarity. (b) The estimated responsivity from data analysis in dependence on total power on the device including background power.

readout is reported in [77] and can in theory lower the readout NEP to $2.5 \times 10^{-18}$ W Hz$^{-1/2}$.

**Spectral Response**

The spectral response of the sample was measured using the schematic shown in Fig. 4.2(b). The device was loaded in the LSPE horn together with a pair of Fluorogold filters and a pair of home made NDFs to block thermal radiation from 300 K background. The high frequency source was a Backward Wave Oscillator. RF absorbing foam was used to block unwanted reflections from cryostat body. A chopper positioned at 45° to the BWO allowed radiation to enter the cryostat or reflected it towards a pyroelectric detector. The output voltage response was normalised against the pyroelectric response to obtain the spectral characteristics of the device. A comparison of measurement and simulation is presented in Fig. 4.11(b). More details are presented in Paper 3.

### 4.4 Parallel CEB arrays

Building parallel connected CEBs into a FSS is an interesting solution to create a low ohmic pixel aimed at matching with the noise impedance of the
4.4. Parallel CEB arrays

SQUID amplifier. A test pixel was fabricated and measured; the basic FSS design of the pixel is similar to the 95 GHz FSS with the addition of two lines running down the length of each column. This allows each element to be connected in parallel. Thus the device works as an distributed absorber consisting of 72 CEBs in parallel and 2 in series. The size of the sample is 11 mm × 11 mm. The measured differential resistance plot of the test pixel is shown in Fig. 4.12(a). For a voltage biased CEB, the point of the maximum current responsivity lies at about \( V = 0.9\Delta E \). At this point the measured device shown a differential resistance of 100 \( \Omega \). This is too high to be matched to a SQUID amplifier but decreasing this value is trivial. The value of the normal state resistance of each tunnel junction of the CEB was 1.75 k\( \Omega \). Decreasing it by a factor of 10 could easily decrease the differential resistance at optimum bias point to 10 \( \Omega \) or lower. This device then could be matched to a SQUID amplifier with an input impedance of 1 \( \Omega \) and a typical current noise of \( \frac{nA}{\sqrt{Hz}} \) by the use of superconducting impedance transformer \[78\]. Using the responsivity figures from Fig. 2.7(b), an amplifier limited NEP of \( 4 \times 10^{-17} \text{ W Hz}^{-1/2} \) can be achieved.

The DC connection in the parallel connected CEBs relies on two bias lines travelling through each unit cell to connect the CEBs in parallel. This can be eliminated by using a schematic as shown in Fig. 4.12(b). The equipotential lines run diagonally across the unit cells. The unit cell itself is more symmetric than, e.g., Fig. 3.11(b). This could reduce spurious resonances in the structure.

![Figure 4.11: (a) Estimated incident and absorbed power as a function of blackbody temperature. (b) Frequency response of the 95 GHz prototype to radiation from a BWO.](image-url)
4.5 Sources of Error

An understanding of the various sources of errors in fabrication, measurements and analysis is important in trying to minimise them. A brief overview of the error source is given in this section.

Figure 4.12: (a) A plot of the derivative of the IV characteristics of the CEB array. (b) An improved schematic of a parallel array. The red dots represent bolometers and the equipotential DC lines run diagonally through the pixel. *Schematic courtesy of Alexander Sobolev.*

In nanofabrication, estimating the thickness of Silicon substrate and the final thickness after plasma etching is a known source of error. Deep Silicon etching is described in Appendix A.2. Several non-destructive methods exist to estimate the substrate thickness but it is the author’s experience that these methods provide differing values for the same substrate. A better method is to dice off a piece of the wafer and use the SEM to measure the thickness. This method is destructive, weakens the wafer and has been a cause of several broken substrates. Estimating the thickness of the substrate after etching is equally difficult. A surface profiler is a common method to measure the etch depth but is unreliable after the etch depth increases beyond 250-300 µm. There is also an inherent dependence on the etch depth as a function of distance from the centre of etching chamber which can cause a shift of the resonance frequency (Fig. 3.4) depending on the position of the pixel on the substrate.

Errors during electrical measurements can range from something as simple as assuming a wrong amplifier gain to something complicated as thermal gradients in the measurement setup affecting the device properties.
4.5. Sources of Error

The latter is particularly dangerous as any thermal gradient can manifest itself as a voltage/current response. These thermal gradients can be set up due to warming up the blackbody while measuring optical response or due to a gradual warming of the cold stage of the cryostat due to depletion of the cooling liquid $^3$He. To estimate the amplitude of these gradients, a sensitive thermometer is integrated in every single chip fabricated during the course of this work and described in Section 5.2.

The stability of the current source and amplifier offset and drifts can create a false output signal which is difficult to track during a short experiment. The measurement of the temperature of the blackbody radiation source is another source of error. In our measurements, a Lakeshore® thermometer is mounted on the blackbody housing to measure its temperature as the blackbody is heated up. The measured value of the blackbody housing may not exactly correspond to the temperature of the black coating due to a difference in thermal inertia of the coating and the copper housing. The emissivity of the coating is assumed to be 0.95 during all estimations in this work but no measurements have been performed to study this parameter. It directly affects the estimations of efficiency of the pixel and the photon noise.

The fitting of measured data to the CEB model can be another source of errors. The assumed value of the volume of absorber can be different from reality due to differing thickness of the insulating oxide layer. We estimate that this error is less than 10%. This is directly connected to estimations of the electron-phonon coupling constant $\Sigma$, the responsivity and the eventual calculation of NEP. The measurement of the temperature of the 0.3 K stage of the cryostat can also introduce an error in the data analysis. While the commercial thermometer on this stage is calibrated, the calibration is a few years old and age related drifts in the measurements can occur.

The description of these errors should not be interpreted as making the presented data and analysis worthless. A large effort has been made to reduce their impact on the device performance. The author would like to take this opportunity to caution future users of this device to consider the information in this section in their own analysis.
Figure 4.13: FSS integrated bolometric designs and measurements. The solid lines represent numerical simulations and the measured data is plotted in circles.

4.6 Summary

Bolometers integrated in a FSS is an attractive distributed-absorber architecture. The present work has been summarised in the plot shown in Fig. 4.13. It is possible to design CEB integrated FSS over a wide frequency range with bandwidths up to 10% of the central design frequency. Spectral measurements agree with high frequency simulations and are supported by analysis of the optical response of the integrated CEB array. High optical efficiency is a desirable characteristics for a bolometer pixel since losses in optical path can be quite high. Efficiencies up to 70% and more have been estimated for fabricated samples in the course of this work. The CEB integrated FSS is thus a very robust architecture and an interesting option for further development.
5.1 Bolometers integrated in slot antennas

The Cold-Electron Bolometer was initially characterised by integrating it in a cross-slot antenna as reported in [79]. The antenna design is described in [80]. The CEB was also integrated in a a twin-slot antenna [81, 82] and also a folded slot antenna. Experiments targeting the understanding of electron temperature, responsivity and dependence of this responsivity on absorbed power and on electron temperature of the device were performed at bath temperatures down to 60 mK. The slot antenna did not play any significant role in these DC experiments and results reported in Paper 4 and Paper 5 are comparable. The RF properties of these devices were investigated by integrating the slot antennas with hyperhemispherical lens and a cold blackbody optical source. This section summarises the results from these experiments.

Resistance ratio and electron temperature

The resistance ratio is the ratio between the differential resistance of a CEB at zero bias and the normal state resistance of the NIS junctions. The normal state resistance is measured at bias point at least 3 times higher than the gap voltage ($eV \geq 3\Delta$). This is necessary since the NIS
nonlinearity extends to this point. Another way to measure the normal resistance of the CEB is to heat up the device to a bath temperature greater than the critical temperature of the superconducting electrodes ($T_{ph} > T_c$). The resistance ratio is an indicator of the electron temperature of the normal metal absorber. Higher electron temperature corresponds to a lower resistance ratio since there exist several electrons in the high energy tail of the Fermi-Dirac distribution of electrons in the normal metal. The hotter electrons cause a current to flow even at extremely low bias. The resistance ratio is also affected by the Dynes parameter $\gamma$ since subgap states in the superconducting electrode can cause electrons to tunnel across the NIS junction at low bias. Thus the resistance ratio indicates the quality of the measurement environment. Analysis of the full SINIS IV curve makes it possible to estimate the electron temperature in the normal metal.

A slot antenna integrated CEB was cooled to bath temperatures down to 60 mK in a dilution refrigerator and IV curves were measured at several bath temperatures. Electron temperature was extracted from this data at each phonon temperature and is plotted in Fig. 5.1(a) along with the corresponding resistance ratio. It is possible to observe that the resistance ratio increases linearly as the bath temperature is lowered until it reaches a saturation point. This saturation coincides with the saturation of the temperature of the electron system. A decrease in the bath temperature below 100 mK does not reflect in a decrease in the electron temperature. The reason lies in the decrease in the electron-phonon in-
5.2. NIS Thermometers

The NIS junction is a very sensitive thermometer and this fact has been recognised since the 1970s [26]. NIS thermometers with a RF readout was proposed in 2003 [83]. In 2008, array of NIS junctions as a sensitive thermometer matched to JFET amplifiers was proposed and developed in different technologies [84, 85, 86]. Sensitivities of $5 \frac{\mu K}{\sqrt{Hz}}$ and better can easily be achieved with commercial room temperature amplifiers. These thermometers are fabricated on every pixel to measure the thermal drift of the cryocooler and correct for any change in the bath temperature. The voltage response of a CEB to phonon temperature for $M$ bolometers in series is $2M \times \frac{dV}{dT_{ph}}$ where $T_{ph}$ is the bath temperature. A typical value of $\frac{dV}{dT_{ph}}$ is $0.25 \frac{\mu V}{mK}$ per junction at $300 \text{mK}$ and large series arrays can create very large bath temperature response which is difficult to get rid of from measurements if the small changes in bath temperature are not precisely measured. As an example, the OLIMPO array of 42 CEBs in series will produce about $21 \mu V$ of response to $1 \text{mK}$ change of bath temperature which is roughly equivalent to an optical response to $105 \text{fW}$ of absorbed power.

NIS array thermometer fabricated on the OLIMPO focal plane wafer utilises the 24th channel of the JFET readout after the first 23 channels have been populated by the pixels on the focal plane. This array has 40 NIS junctions in series with 4 in parallel. This allows impedance matching to cold JFET amplifiers that are used for the rest of OLIMPO readout. Similar thermometers are fabricated on test pixels and other CEB samples.
Measurements from a typical thermometer are shown in Fig. 5.2. The sensitivity of the thermometer to changing bath temperature is measured by current biasing the device and sweeping the bath temperature. Fig. 5.2(a) shows the voltage response of the thermometer and a sensitivity of 12 $\mu\text{V/mK}$ is estimated. Fig. 5.2(b) shows the IV characteristics of this thermometer and noise as a function of bias. This noise was measured at 37 Hz using room temperature commercial amplifier AD743. The Noise Equivalent Temperature (NET) is defined as the lowest measurable temperature corresponding to noise measured in 1 Hz bandwidth. For the device described above, using $\text{NET} = \frac{\text{Noise}}{\text{Sensitivity}}$, the best estimated $\text{NET} = 1.5 \frac{\mu\text{K}}{\sqrt{\text{Hz}}}$.

This value of NET is sufficient for tracking the changes in bath temperature in the laboratory or on board the balloon-borne experiment. Further improvement in the thermometer sensitivity is possible using cold JFET amplifiers and a low noise current bias system.

**Comparison with bolometers**

Since a thermometer is a NIS junction based device, it can be compared with a bolometer. Thermometer NIS junctions have large normal state resistance which lowers the current flowing through the junction and suppresses local cooling of the electron system of the normal metal. The job of a thermometer is to measure the phonon temperature and local cooling can introduce errors in this measurement. The normal metal electrode of a NIS thermometer needs to be thermalised to the phonon temperature and usually has a large volume.
5.2. NIS Thermometers

Figure 5.3: Comparison between a thermometer and bolometer. Electron cooling increases the differential resistance of a bolometer with a small volume of absorber when biased between $V = 0.5\Delta_e$ to $V = 0.95\Delta_e$. In contrast, the thermometer absorber volume and the normal state resistance of the tunnel junction are much higher and suppress electron cooling.

SINIS bolometers on the other hand are limited in the volume of normal metal. As a consequence, the CEB is smaller in size compared to a thermometer. The small normal metal volume decreases the heat flow from electron to phonon systems at low phonon temperatures. This decoupling is also responsible for possibility of electron cooling.

The Fig. 5.3 shows the differential resistance of the measured IV curves of a thermometer and a bolometer. As expected, the bolometer shows signature of electron cooling as the bias approaches the energy gap of the electrode. This supports the “Cold-Electron” part of the Cold-Electron Bolometer.
Summary and future prospects

Cold-Electron Bolometer is a superconducting detector for ultra high sensitivity applications. It avoids some drawbacks of other comparable bolometric detectors and has proved to be versatile in matching to available antenna systems and readouts. In this work the DC and RF properties of the CEB have been studied. The Frequency Selective Surface is sensitive to only one frequency band and CEBs were integrated in the FSS to form a band limited distributed absorber. These FSS based detectors at 345 GHz have been successfully tested for the OLIMPO telescope focal plane array. Responsivities of the order of $10^8 \, \text{V/W}$ have been measured at 300 mK. Test pixels at 95 GHz were fabricated and characterised and an efficiency of about 70% has been estimated.

The Frequency Selective Surface based bolometric design can be used in many different future applications. Since the FSS based design can be adopted with ease for any frequency band in the mm/sub-mm range and is mechanically very robust, it can prove to be competitive for future balloon or space borne telescopes. The FSS can transmit, reflect or diffract radiation and a bolometric detector scheme exploiting these properties is feasible. Multilayer FSS sensitive to more than one frequency bands are also an attractive next step for this technology.

The prospects of the CEB are also promising. Due to its small active area, the CEB can avoid the problem of Cosmic Ray contamination of measurements and this alone makes it worthwhile to use this detector instead of other large area bolometers. The series/parallel connections of
the CEB make it possible to create high or low ohmic pixels which can be impedance matched to JFET or SQUID readout. The latter possibility is very attractive as it allows multiplexing of a large number of devices. The capacitance of the NIS junction allows one to build resonators with the inductive element provided by kinetic inductance of a strip of superconducting material like niobium nitride. Resonating CEBs could be easily used with a broadband antenna to couple to multiple narrow frequency bands reducing the need for on-chip RF filters. Low sensitivity of the CEB to magnetic fields and moderate sensitivity to variations in phonon temperature opens up many possibilities for this superconducting detector.
The fabrication of the current version of Cold-Electron Bolometer arrays has been detailed in [87]. The antennae, contact pads, resistors and capacitors can be fabricated by photolithography or electron beam lithography while the CEBs are fabricated exclusively by electron beam lithography. We chose a mixture of the two methods; alignment markers, resistors, capacitors and CEBs are fabricated with ebeam while contact pads are fabricated using a photo mask. A photolithography process is used for the mask for deep Silicon etching.

The nanofabrication was a typical bottom-up approach. Each part of the whole device was fabricated as a “layer” - the alignment marks layer (first), resistors layer (second), capacitors layer (optional third), contact pads (fourth) and the CEBs (fifth). All the layers were fabricated with the sequence of resist spinning - exposure - development - metal deposition - liftoff. A double side alignment procedure is used to align the FSS based pixels with an etch mask for patterning the Silicon membrane.

Fabrication “recipes” for different resist systems are mentioned below. One chooses the correct recipe depending on exposure source (i-line photolithography or electron beam source) and required resolution.
A.1 Resist Systems

LOR 3A - S1813 resist system

- Dehydration bake: 5 minutes on hotplate at 190°C to 200°C
- HMDS primer, spin coat at 3000 RPM for 10 seconds
- LOR 3A, spin coat at 3000 RPM for 45 s, thickness = 350 nm
- Prebake: 5 minutes on hotplate at 190°C to 200°C
- Spin coat S1813, 3000 RPM, 45 seconds, thickness = 1500 nm
- Prebake: 2 minutes on hotplate at 110°C
- Expose 10 seconds at $6 \text{ mW/cm}^2$
- Develop in MF 319 for 90 seconds
- Rinse in water and blow dry with N$_2$ gun
- Descum (recipe: ash$_{10}$s, 50 W, 250 mTorr, 10 sccm O$_2$ flow)
- Deposit metal
- Liftoff in Shipley 1165 Remover or mr-REM 400 at 50°C until all unwanted metal has lifted off
- Rinse off with IPA and rinse in deionised water

AZ4562 resist system

- Dehydration bake: 5 minutes on hotplate at 190°C to 200°C
- HMDS primer, spin coat at 3000 RPM, 10 seconds
- AZ4562, spin coat at 4000 RPM for 30 seconds, thickness = 6200 nm
- Prebake: 3 minutes on hotplate at 100°C
- Expose 10 seconds at $6 \text{ mW/cm}^2$
- Develop in MF 322 for 2-3 minutes, until it stops “bleeding” then add about 20 seconds
- Rinse in water and blow dry with N$_2$ gun
- Hardbake: 60 minutes in oven at 120°C
AZ 1512HS resist system

- Dehydration bake: 5 minutes on hotplate at 190° C to 200° C
- AZ 1512HS, spin coat at 3000 RPM for 45 seconds, thickness = 1400 nm
- Prebake: 1 minute on hotplate at 100° C
- Expose 4.7 seconds at 6 mW/cm²
- Develop in MF 322 for 1 m
- Rinse in water and blow dry with N₂ gun
- Hardbake: 60 minutes in oven at 120° C

LOR 3A - UV-5 resist system

- Dehydration bake: 5 minutes on hotplate at 190° C to 200° C
- HMDS primer, spin coat at 3000 RPM for 10 seconds
- LOR 3A, spin coat at 3000 RPM for 60 seconds, thickness = 350 nm
- Prebake: 5 minutes on hotplate at 180° C
- UV-5 (0.8) spin coat at 3000 RPM, 60 seconds, thickness = 800 nm
- Prebake: 2 minutes on hotplate at 130° C
- Expose with electron beam at 50 keV acceleration voltage at a dose of 16 μC/cm² for uncorrected patterns
- Postbake: 90 seconds on hotplate at 130° C
- Develop in MF-24A for 100 seconds
- Descum (recipe: ash_10s, 50 W, 250 mTorr, 10 sccm O₂ flow)
- Evaporate metal
- Lift off in Shipley 1165 Remover or mr-REM 400 at 50° C until all unwanted metal has lifted off
Appendix A. Fabrication

For good adherence of LOR 3A on the wafer, a thin layer of HMDS primer is spun for 20 seconds. The LOR 3A spun at 3000 RPM leaves a 350 nm thick layer of the polymer on the wafer. A layer of UV-5 (diluted to 0.8% in Ethyl Lactate) is spun at 3000 RPM for a layer thickness of ca. 850 nm. MF-24A develops both UV-5 and LOR 3A. The rate of dissolution of LOR 3A is larger than UV-5, hence an “undercut” is formed in the resist system which facilitates metal liftoff. After deposition of the chosen metals, the wafer was put in Shipley Microposit Remover 1165. The LOR 3A absorbs the remover liquid and swells to hundreds of times its thickness. This creates an enormous tension on the top metal layer and breaks it apart and the rests float away in the liquid. The wafer can then be cleaned in isopropanol and water to remove all traces of the Remover 1165. Finally, any remaining organic residues can be removed by treating the wafer in a mild oxygen plasma - 50 W for 30 seconds.

Copolymer-ZEP resist system

- Dehydration bake: 5 minutes on hotplate at 190°C to 200°C
- MMA (8.5) MAA EL10 (Copolymer), spin coat at 3000 RPM, 60 s, thickness = 410 nm
- Prebake: 5 minutes on hotplate at 160°C
- ZEP 520A (1:1), spin coat at 2000 RPM for 60 s, thickness = 140 nm
- Prebake: 5 minutes on hotplate at 150°C
- Expose with electron beam at 100 keV acceleration voltage at a dose of 400 $\mu\text{C/cm}^2$ for manually corrected patterns or a dose of 160 $\mu\text{C/cm}^2$ for proximity corrected patterns with Proxecco or Beamer packages.
- Develop ZEP in Hexyl Acetate for 33 s
- Develop Copolymer in MIBK:IPA (1:1) for 6 minutes 45 seconds
- Descum (recipe: ash _10s, 50 W, 250 mTorr, 10 sccm O$_2$ flow)
- Evaporate metal
- Liftoff in Shipley 1165 Remover or mr-REM 400 at 50°C until all unwanted metal has lifted off
A.2. Device Layers

The resist system for the CEB layer is the high resolution electron beam resist ZEP (diluted 1:1 in Anisole). The resolution is process dependent but single lines with widths of 10 nm have been demonstrated with this resist. The liftoff layer in this system is the MMA (8.5) MAA EL10 (10% solids in Ethyl Lactate). This polymer is spun on the wafer at 3000 RPM for a layer thickness of 400 nm. The ZEP resist is spun next at 2000 RPM and for a layer thickness of 150 nm. After exposure at 400 $\mu C/cm^2$ (manual proximity correction), the ZEP is developed in Hexyl Acetate for 35 seconds and the MMA copolymer is developed in MIBK:IPA (1:1) for 6 minutes 45 seconds for a controlled undercut size of 250 nm. This allows the punch through of copolymer below ZEP “bridges” and allows for tilted stage metal evaporation (shadow evaporation). After metal evaporation, the unwanted metal is lifted off in Acetone or warm Remover 1165 (50$^\circ$ C) and the wafer is cleaned in isopropanol and water. The devices are then ready to be measured.

Niobium and Niobium Nitride etch recipe

Niobium and niobium nitride can be etched with the fluorine chemistry in a plasma etching system. The typical parameters for a NF$_3$ plasma are a flow rate of 50 sccm, a pressure of 10 mbar and a forward (platen) power of 50 W. The etch rates can be varied by varying the plasma power. This recipe is useful for etching the silicon nitride membranes and also for etching the niobium nitride based Resonance Cold-Electron Bolometers proposed in 2014 [53].

A.2 Device Layers

Alignment marks

The first layer consists of alignment marks and uses the LOR 3A - UV-5 resist system. The alignment marks are cross shaped made of a bilayer of titanium/gold (Ti/Au) of thickness 10 nm and 70 nm. The titanium improves the adhesion of gold to the silicon substrate while the gold marks provide optical and electron beam backscatter contrast for alignment. A negative cross can also be used for better optical contrast for the double side alignment procedure.
Resistors

The resistors are fabricated as the second layer. Using the LOR 3A - UV-5 resist system, the resistor meander is exposed and developed on the wafer. The resistor material is a bilayer of 10 nm of titanium and 5 nm of palladium with an effective sheet resistance of $100 \, \Omega/\square$. We have managed to produce resistors with resistances up to $10 \, \text{M}\Omega$. We have observed no difference in the resistance values at room temperature or at cryogenic temperatures.

![Figure A.1](image1.png)

Figure A.1: (a) Scanning Electron image of “bridges” in an evaporation mask. The free hanging structure in the centre of the image allows an electrical discontinuity between two regions of thin metal film evaporated at normal incidence. The brighter top layer hangs over the darker bottom polymer layer. This is called the undercut and facilitates clean liftoff of evaporated metal (b) A zoomed in view of the bridge. These structures are created in Germanium using the hard mask technology but the ZEP bridges described on this page look and function in the same way. The scale bar in both the images is 100 nm.

Capacitors

Capacitors are optional components used mainly in slot antenna based devices. For DC coupling, a cross slot antenna is cut into 4 parts and separated by capacitors that offer low RF impedance but are open circuited at DC. The dielectric for the capacitors is a thin (~5 nm) layer of silicon nitride ($\text{SiN}_x$) deposited with PECVD and patterned with UV-5 resist and electron beam lithography. The results are mixed; yield of working devices is poor and this fabrication routine needs to be optimised further.
Insulator

Insulating layers are generally needed for overcross of DC lines on the wafer. We pattern the LOR 3A - UV-5 system where an overcross is required and deposit 35 nm of silicon dioxide ($\text{SiO}_x$). This process is very robust and the dielectric retains its qualities even after multiple cooling cycles.

Antenna elements

Antenna elements including FSS elements are fabricated in thick gold to reduce RF losses. The pattern is exposed using the LOR 3A - UV-5 resist system and a trilayer of 10 nm titanium, 250 nm gold and 30 nm palladium is evaporated and unwanted metal lifted off. The Titanium functions as adhesion layer between gold and silicon substrate. The top palladium ensures low contact resistance between gold and eventual aluminium superconducting layer by avoiding formation of intermetallic products between these two metals (also called “white/purple plague”).

Bolometers

Cold-Electron Bolometers are evaporated using trilayer shadow evaporation technology. After patterning the device using the Copolymer-ZEP resist system, the normal metal layer consisting of a bilayer of 7 Å Iron and 12 nm Aluminium is deposited at an angle perpendicular to the plane of evaporation. This normal metal layer is oxidised for 15 minutes at a pressure of 10 mbar in presence of pure $\text{O}_2$. Superconducting electrodes of total thickness 150 nm are evaporated at angles of $+45^\circ$ and $-45^\circ$ by tilting the sample stage with respect to the plane of evaporation. The metal is lifted off in Acetone or Shipley Remover 1165 warmed to 50°C. Instead of iron, nickel-iron, cobalt or chromium (II) oxide ($\text{CrO}_2$) can also be used. These impurities are ferromagnetic and suppress superconductivity in the aluminium layer.

Deep Silicon Etch

The FSS design demands that the Silicon substrate be thinned down to a thickness determined by high frequency simulations. These membranes are patterned on the side opposite to the FSS array. Initially, a 400 nm thick layer of aluminium is sputtered on the membrane side of the wafer after cleaning that side in oxygen plasma. Double side alignment is used to position the optical mask with the membrane shape and patterned using the
Appendix A. Fabrication

Figure A.2: (a) The CAD schematic of the 345 GHz focal plane wafer. (b) Optical image of the wafer integrated with the readout PCB. The size of the wafer is 40 mm × 40 mm. *Image courtesy of M. Salatino.*

S1813 resist system. The unwanted aluminium is dissolved in aluminium etch solution. The wafer is then mounted in the DRIE machine which is a plasma etch system using the Bosch® process to anisotropically etch Silicon to the required depth. The back side of the wafer (the side that will hold the FSS elements) is protected using a photoresist layer hardbaked in oven for 30 minutes. The etch depth is monitored using a surface profiler.

A.3 OLIMPO 345 GHz and 480 GHz focal plane array

The OLIMPO focal plane wafer is designed in a CAD system. The focal plane is 40 mm × 40 mm containing 23 pixels and one NIS thermometer fabricated on a 3-inch intrinsic high ohmic (>2 kΩcm) Silicon wafer. Each pixel is biased through two 10 MΩ resistors fabricated using the thin film meander technology. Each pixel has two lines for bias current connecting the external voltage source to the pixel through the bias resistors. The pixel is read out suing two lines connected to cold JFET amplifiers. Thus each pixel has 4 contact lines terminating on the edge of the focal plane wafer in Gold contact pads of the size 3000 µm × 700 µm. The wafer is surrounded
A.3. OLIMPO 345 GHz and 480 GHz focal plane array

Figure A.3: (a) OLIMPO 480 GHz focal plane wafer. (b) The back side of the wafer showing the etched membranes. The size of the wafer is 40 mm × 40 mm.

by a printed circuit board (PCB) with gold plated copper bond pads of the same size next to the pads on the wafer. Wire bonds connect the PCB and the wafer connecting the pixels with the rest of the readout system. Cross shaped marks are also fabricated to facilitate alignment between successive layers. The unused space on the wafer is filled with test pixels that are used for laboratory tests. The fabrication of the wafer proceeds as follows:

- Patterning of alignment marks on one side of the wafer
- Patterning the mask for silicon etching on the back side of the wafer using double side alignment
- Deep silicon etch using the Bosch® process.
- Patterning of meander resistors on the front side of the wafer
- Patterning bond pads, connecting lines and FSS elements on the front side of the wafer
- Patterning CEBs between the FSS elements
- Scribing the wafer using a diamond pin to separate the test pixels from the focal plane
A.4 The OLIMPO cryogenic mounting

As noted earlier, the OLIMPO focal plane was fabricated on a 3-inch (75 mm diameter), intrinsically doped, high resistivity silicon wafer. The dimensions of the focal plane (40 mm × 40 mm) meant that there was enough space to fabricate 24 single pixels of the same specifications as the pixels on the focal plane. Since the single pixels and the focal plane was fabricated in the same fabrication run, the RF and DC properties of the single devices are expected to match those of the devices on the focal plane. A schematic of the full wafer is shown in Fig. A.2. The central 23 squares correspond to the focal plane pixels while the surrounding 24 single test pixels can also be seen.

![Figure A.4](image)

Figure A.4: (a) The OLIMPO cryogenic system. (b) OLIMPO optical path inside the cryostat showing the relative position of various frequency bands. (c) Photograph of the cold optics. Images courtesy of S. Masi and P. de Bernardis, Rome University.

The OLIMPO readout is a 24-channel cold JFET voltage readout
system cooled to 110 K for the proper operation of the JFETs at their lowest voltage noise point [75]. The pixels are current biased with on chip 10 MΩ resistors shown in blue in Fig. A.2. Six pixels are parallel biased with the same voltage bias circuit. The individual resistors shown create the proper current bias. The individual readout lines connect to a pair of JFET differential amplifiers in the voltage readout.

In order to integrate the 23 pixels in the OLIMPO focal plane, a suitable PCB and a mechanical support have been developed. In the OLIMPO readout electronics, the detectors are powered with a bias voltage and the same input bias is shared between six detectors. The pads dimensions and steps have been optimized to assure reliable wire bonding with the array pads. The mechanical support has been developed to be "plug and play", allowing a simple integration in the focal plane and satisfying all the mechanical constraints of the OLIMPO focal plane and optics box. It comprises several elements which are shortly described starting from the first met by the incoming radiation. A horns array, each feeding a CEB pixel, detect the RF signal; each horn has been designed as shown in Fig. 3.8. On top of the horns array, a filter provides additional spectral selection of the incoming radiation. The horns array and the central waveguides are kept together by a suitable copper support which lodges, also, the CEBs array. Suitable pins align the horns with the corresponding waveguides. A precise flat surface located at a distance of 160 µm away from the array substrate behaves as a backshort; its positioning is aligned by precise machined copper cylinders which are mounted on the copper support. Another copper support holds the detector wafer and provides the base over which a small box, containing all the wiring from the PCB, is mounted. All the constituting elements, apart from the horns array, are gold plated to increase their thermal conductivity.

A.5 145 GHz and 95 GHz prototype devices

The 145 GHz prototypes are fabricated similar to OLIMPO prototypes. They are fabricated on an intrinsic high ohmic 3-inch Silicon wafer. A CAD schematic of the 145 GHz prototype is shown together with the finished sample in Fig. 4.8 and a zoomed view of a FSS ring is shown in Fig. A.5. The process flow is as follows:

- Pattern alignment marks on one side of the wafer
Figure A.5: (a) Optical image of a single ring shape fabricated from thick gold film. The bright yellow patches are superconducting aluminium electrodes. (b) Zoomed in image of the CEB. The scale bar on the right is 10 µm. The bright yellow colour corresponds to superconducting aluminium film and the CEB can be seen in the gap. A thin normal metal trap layer is seen below the electrodes.

- Pattern meander bias resistors
- Pattern contact pads and FSS elements
- Pattern CEBs within the FSS elements
- Scribe the wafer into individual chips with a diamond pin

A.6 Slot antennas

Experiments with slot antennas centred around the cross-slot antenna and the twin slot antenna. The twin slot antenna had 3 CEB detectors at the centre of the coplanar line feeding the twin slots. The fabrication consisted of one CEB layer and one layer for fabricating the antenna. An optional layer for fabrication of on-chip resistors was considered. An image of this antenna and a zoomed in version is shown in the top panel of Fig. A.6.

The cross-slot antenna described in Paper 5 required five device layers - alignment marks, resistors, capacitor, antenna and the CEB structure. There were 3 CEBs in each of the 4 slots. This complicated structure is shown in the centre panel of Fig. A.6.
A.6. Slot antennas

Figure A.6: Optical and scanning electron images of the CEB integrated in twin slot antenna (top), cross slot antenna (centre) and the folded slot antenna (bottom).

The CEB was also integrated in the folded slot antenna as shown in the bottom panel of Fig. A.6. This antenna was designed by Y. Karandikar, then at the Microwave Electronics Lab in Chalmers University. While the experiments with this antenna gave interesting results, they are beyond the scope of this thesis.
Summary of Appended Papers

Paper 1
A Frequency Selective Surface based focal plane receiver for the OLIMPO balloon-borne telescope
Mahashabde, S., Sobolev, A., Bengtsson, A., Andrén, D., Tarasov, M. A., Salatino, M., de Bernardis, P., Masi, S., & Kuzmin, L.S.
This paper describes the design, fabrication and characterization of a Frequency Selective Surface (FSS) based planar bolometric architecture to be used as a detector on the OLIMPO balloon telescope. This paper demonstrates the first experimental characterization of FSS based Cold-electron Bolometer (CEB) arrays and the frequency selective nature of such devices. Contribution: SM designed and fabricated the devices. SM and MAT measured the devices. SM, AB, DA analysed the devices. SM also wrote the manuscript.

Paper 2
Planar Frequency Selective Bolometric Array at 350 GHz
Mahashabde, S., Sobolev, A., Tarasov, M. A., & Kuzmin, L. S.
This paper describes the general design principles for FSS based detector array architecture. It explores the modelling of these arrays using a microwave equivalent circuit approach. A series of RF simulations are described in the paper demonstrating the tunability of the architecture. Optical response measurements with a blackbody radiation source demonstrate the optical coupling of the devices along with spectral measurements. Contribution: SM and AS designed the devices. SM fabricated the devices. SM and MAT did measurements. SM analysed the data and
Summary of Appended Papers

wrote the manuscript.

**Paper 3**

**A distributed-absorber Cold-Electron Bolometer single pixel at 95 GHz**

*Mahashabde, S., Tarasov, M. A., Salatino, M., Sobolev, A., Masi, S., Kuzmin, L. S. & de Bernardis, P.*

This paper describes the design, fabrication and characterization of a prototype 95 GHz FSS based Cold-Electron Bolometer array which is a possible candidate for the LSPE balloon telescope for the measurement of the curl component of CMB polarization (B-mode). The FSS based array is integrated with a multimode horn designed to couple with multiple space modes for improved survey sensitivity of the telescope with low pixel count at the expense of angular resolution.

**Contribution:** SM designed and fabricated the array and measured it with the help of MAT. SM analysed the optical response data. SM also wrote the manuscript.

**Paper 4**

**Power Load and Temperature Dependence of Cold-Electron Bolometer Optical Response at 350 GHz**

*Tarasov, M. A., Edel’man, V. S., Mahashabde, S., & Kuzmin, L. S.*

This paper describes the integration of the Cold-Electron Bolometer in a twin slot antenna and optical measurements using a blackbody source and immersion Silicon lens. Electron temperature of the bolometer absorber at different bath temperatures was estimated. Optical responsivity of the device was estimated as a function of incident power at different bath temperatures and power levels.

**Contribution:** MAT and SM designed the devices and SM fabricated them. SM helped with analysis of the data. SM also partly wrote the manuscript and helped in responding to referees.

**Paper 5**

**Optical Response of a Cold-Electron Bolometer Array Integrated in a 345-GHz Cross-Slot Antenna**

*Tarasov, M. A., Kuzmin, L. S., Edel’man, V. S., Mahashabde, S., & de Bernardis, P.*

This paper described the integration of the Cold-Electron Bolometer in a cross-slot antenna. The system was measured with a blackbody source and a Backward Wave Oscillator with the measurement bandwidth defined by metal mesh filters. A study of polarization sensitivity of the cross-slot
antenna based bolometer was made. The dependence of voltage response of
the device to bath temperature and incident power was measured. Dynamic
range of the device was demonstrated to be 43 dB between the saturation
level and the noise floor.

**Contribution:** The devices were designed by MAT and fabricated by SM
who also helped with measurements and writing the manuscript.
Bibliography


[74] http://www.terahertz.co.uk/.


A Frequency Selective Surface based focal plane receiver for the OLIMPO balloon-borne telescope

Mahashabde, S., Sobolev, A., Bengtsson, A., Andren, D., Tarasov, M.A., Salatino, M., de Bernardis, P., Masi, S., & Kuzmin, L.S.

A Frequency Selective Surface based focal plane receiver for the OLIMPO balloon-borne telescope

Sumedh Mahashabde, Alexander Sobolev, Andreas Bengtsson, Daniel Andrén, Michael Tarasov, Maria Salatino, Paolo de Bernardis, Silvia Masi, and Leonid Kuzmin

Abstract—We describe here a focal plane array of Cold-Electron Bolometer (CEB) detectors integrated in a Frequency Selective Surface (FSS) for the 350 GHz detection band of the OLIMPO balloon-borne telescope. In our architecture, the two terminal CEB has been integrated in the periodic unit cell of the FSS structure and is impedance matched to the embedding impedance seen by it and provides a resonant interaction with the incident sub-mm radiation. The detector array has been designed to operate in background noise limited condition for incident powers of 20 pW to 80 pW, making it possible to use the same pixel in both photometric and spectrometric configurations. We present high frequency and dc simulations of our system, together with fabrication details. The frequency response of the FSS array, optical response measurements with hot/cold load in front of optical window and with variable temperature black body source inside cryostat are presented. A comparison of the optical response to the CEB model and estimations of Noise Equivalent Power (NEP) is also presented.

Index Terms—Cold Electron Bolometer, Frequency Selective Surface, OLIMPO

I. INTRODUCTION

Frequency selective surface is an artificial arrangement of simple metallic repeating patterns that provide a resonant interaction with incident electromagnetic wave. The interaction manifests as band-pass, band-stop, reflecting or absorbing behaviors [1]. A large number of simple repeating motifs have been used over the years in the form of crosses, squares, circles and hexagons, arranged either on planar substrate or as free standing metallic membranes that are used for quasioptical mesh filters [2]. The band-pass filter is usually a mesh design with narrow bandwidth and is a candidate for integrating bolometric detectors in. A number of attempts have been made to use FSS-based filters fabricated on membranes with a working principle that they couple to incident power in a given bandwidth heating the wideband sensitive membrane [3] [4] and the increase in the membrane temperature is detected by a Transition Edge Sensor. Even multi-color radiometers have been fabricated and tested based on this idea [4] [5].

The authors of this paper have been involved with the Cold Electron Bolometer Detector [6] which is a two terminal superconducting detector that uses two Superconductor-Insulator-Normal metal tunnel junctions to couple power to a normal metal nanoabsorber. The junctions are also used to measure the temperature change of the nanoabsorber. Most important feature of the CEB architecture is that the same two junctions cool of the electron system of the absorber using the bias current which provides negative electrothermal feedback. In this paper we describe detector architecture for the OLIMPO experiment [7]. In our planar pixel, we use the FSS approach for quasioptical coupling to incoming signal power from space and detection is provided using the CEB detector. The CEB is a two terminal detector and we’ve managed to arrange it into the repeating FSS motif e.g. annular shape, meander shape and match the impedance of the CEB to the embedding impedance seen by the CEB in such a way that RF currents flow through the CEB heating the electron system of the normal metal and creating a response signal. Such an integration of the planar imaging array with the FSS results in absorbing of the incoming radiation by the detector only in a narrow frequency band. The readout for this response uses the same FSS unit cells connected in series and parallel [6] [8] such that the Noise Equivalent Power (NEP) of the system together with the readout amplifiers is minimized.

The OLIMPO mission is a long duration balloon-borne experiment with a f/3.44 telescope and with detectors in four frequency bands cooled down to about 300mK. The goal of the experiment is photometric and spectrometric observations of the Sunyaev–Zel’dovich effect from galaxy clusters. The Band 3 of the telescope has 23 pixels in the focal plane. Commercial quasioptical mesh bandpass filters will be used to define the bandwidth from 330 GHz to 365 GHz. The detectors are expected to have a NEP to be lower than photon noise. The estimated background power loads are 38 pW and 66 pW in the photometric and the spectrometric configuration, respectively, which sets the background noise level. The
readout for CEBs will be cold JFET amplifiers similar to [9] [10].

II. FOCAL PLANE ARRAY OF DETECTORS

A. FSS with integrated CEB detectors

We describe here the unit cell of the FSS structure the CEB detectors have been integrated in. It is an annular shape with extended lines on all 4 sides. One opposite pair of lines terminate at a short distance from the unit cell edge such that the other pair of lines can facilitate dc connections to neighboring cells in only one direction (X or Y). This pattern is designed to be fabricated on a Silicon substrate of calculated thickness backed with a backshort. The radiation is coupled from the Silicon side similar to traditional lens antennas. The FSS surface together with the substrate and backshort form a resonant interference filter that couples to submillimetre radiation, where the backshort and the substrate tune out the reactance of the FSS layer. This structure has been simulated in the commercial 3D electromagnetic simulation package HFSS using periodic boundary conditions and illuminated by a plane wave excitation using a Floquet port. The unit cell structure is shown in Fig. 1 with four integrated detectors in the arms of the annular element. The return loss ($S_{11}$) plot is shown in Fig. 2. In our model the surface loss of the metal parts made of golden films was taken into account. Representing the four CEB-detectors each by a lumped port with the same impedance, we have found that the amount of power dissipated in the gold electrodes is negligible compared to the power absorbed in the detectors. So, the relation $\sum_{i=1}^{4} S_{1i}^2 + S_{11}^2 = 1$ is satisfied, where $S_{1i}$ is the power coupled to the $n$-th detector. Thus, $S_{11}$ can be used to describe the optical coupling to the detectors while simulating the complete pixel with hundreds of lumped elements.

![Fig 1. The unit cell of the FSS on the left and close up view of the annular mesh element on the right. The Floquet excitation is arranged at the bottom of the unit cell. The grey solid is the Silicon substrate with the annular shape visible on it. The top is capped by the backshort. Periodic boundaries are arranged on each parallel face to simulate an infinite array and the phase difference between the periods is used to calculate the angle dependent absorption of the FSS. The 4 bolometers (as four lumped elements) are arranged between the gaps of the annular element. The thin lines facilitate DC connection to neighboring pixels but are also an integral part of the FSS, being included in the RF simulations.](image1)

The best case coupling has been calculated for a unit cell with a silicon substrate thickness of 141 $\mu$m, backshort distance of 160 $\mu$m and a unit cell pitch of 510 $\mu$m. The design has been optimized such that the best coupling is obtained for a real part of detector impedance of 50 $\Omega$ and an imaginary part of impedance corresponding to a capacitance of 50 $fF$. These are very common parameters in the CEB fabrication.

B. Cold stop

Planar incoherent arrays of detectors can couple to incident radiation over a large solid angle and the advantages and disadvantages have been analysed in [11]. In the current design, we have made preliminary calculations of the absorption of an arbitrarily polarised wave incident on the unit cell at different angles. Once the return losses $S_{11}(TE)$ and $S_{11}(TM)$ for TE and TM modes are known from numerical simulations, we can estimate the angle dependent absorption of a finite pixel size by the formula $P(TE,TM) = (1-\cos^2\theta)\cos^2\theta$. The factor $\cos^2\theta$ accounts for the different pitch to the incoming radiation incident at angle $\theta$ relative to the focal plane normal vector. The result is shown in Fig. 3. Here we neglected the edge effects and obtained the beam width 60° at the level – 3 dB. It is a narrower beam compared to that defined simply by $\cos^2\theta$ function. The reason is that when the incident wave is not normal to the array plane ($\theta=0$) the excitation signal has a phase delay across the unit cell that can be represented as an additional surface reactance. This reactance increases with $\theta$ and reduces the impedance match.

![Fig 2. The $S_{11}$ plot of the FSS unit cell for two orthogonal modes of the Floquet port.](image2)

![Fig 3. The angle dependent absorption of the FSS with integrated CEB detectors.](image3)
For a pixel mounted in the cryostat of the OLIMPO telescope, the “sidelobes” should not illuminate any surface of the cryostat that could potentially radiate some power in the bandwidth of the filters. Due to thermal budget restrictions, a black absorbing surface nearest to the detectors could not be considered. Instead, a new design of an array of horn based cold apertures was developed to limit the angle of visibility of the pixel. These apertures would be mounted on the 300 mK stage of the cryostat atop the pixels. This aperture is shown in Fig. 4, consists of two back to back horns connected together with a 2 mm long section of a circular waveguide of diameter 0.9 mm that is slightly overmoded (5 modes) at the frequencies of interest. The top part of the cold stop can be imagined as a traditional horn illuminating the telescope, and was simulated as such in the commercial package HFSS. The bottom part of the cold stop can be simulated by assuming a waveguide port at the circular waveguide end exciting all possible waveguide modes and propagating the power in the direction of the FSS pixel. The return loss ($S_{11}$) for each mode excited in the waveguide is a good indicator of the optical coupling of the pixel.

We have simulated the cold stop + FSS in HFSS. The simulations of the top part of the cold stop indicate that it can illuminate the telescope optics reasonably well with an on-axis directivity of 23.4 dB and half power beam width of 12°. This directivity pattern is shown in Fig. 5 (top). The simulation of the bottom part of the cold stop with the FSS also shows promising results. For the full pixel of size ca. 3 mm x 3 mm, the optical coupling is better than 50% over the whole band. These results are shown in Fig. 5 (bottom).

C. DC design

The DC design for the integrated planar array follows from [12] [13]. Depending on the number of unit cells required to effectively cover the pixel area under the cold stop, the bolometers can be connected in series/parallel to match the noise impedance of the cold JFET amplifiers. In the current design, the cold stop limits the area of the pixel to a circle with a diameter of 3 mm where 21 unit cells of the annular shape can be fitted, each containing 4 bolometers, giving a total of 84 bolometers. The performance of the array can be simulated by modelling the performance of 1 CEB and scaling the responsivity to M array elements each experiencing M times less incident power. This analysis can be done using the heat balance equation [13] [14] [15] that equates power incoming into the normal metal absorber of the CEB and the power leaving the absorber due to bias current at quasi steady state.

$$2P_N + 2\beta P_S - \Sigma \Lambda (T_e^5 - T_{ph}^5) + I^2 R_a + \frac{P_0 + \delta P(t)}{M} = 0 \quad (1)$$

Here, $P_N$ is the power deposited in the normal metal due to bias current, $P_S$ is the power deposited in the superconducting electrode, $\beta$ is a parameter [16] that refers to the fraction of power deposited in the superconducting electrode that returns back to the normal absorber. $\Sigma \Lambda (T_e^5 - T_{ph}^5)$ is the heat flow from electron to phonon subsystems in the absorber, $\Sigma$ is the electron-phonon coupling constant which is material dependent, $\Lambda$ is the volume of the normal absorber, $T_e$ is the electron temperature of the absorber and $T_{ph}$ is the bath temperature. $I$ is the bias current, $R_a$ is the resistance of the absorber, $P_0$ is the background power on the pixel in steady state while $\delta P(t)$ is the incident signal power. Assuming that the signal power is a very tiny variation on top of the background power (this is especially true for balloon borne experiments with very large atmospheric power loads), the
pixel dc parameters can be estimated using the steady state part of the heat balance equation.

The current through a SIN junction is dependent on the number of occupied and unoccupied states in each of the metals and can be expressed as [14]

\[ I = \frac{1}{e^2 R_N} \int_{-\infty}^{\infty} v(E)(f_N(E - eV) - f_S(E))dE \]

(2)

where \( e \) is the electron charge, \( R_N \) is the normal resistance of the junction and \( V \) is the voltage across the same junction. \( v(E) \) is the Dynes density of states [17] for the superconductor and \( f_N(E) \) is the Fermi-Dirac distribution for the normal metal which depends not only on the energy but also on the temperature of the electron subsystem in the normal metal. This dependence of temperature is what we correlate to absorbed power in the normal metal. \( f_S(E) \) is the Fermi-Dirac distribution for the superconductor and in general it will be different from \( f_N(E) \) since they can have different electron temperatures.

The tunneling electrons in the SIN junction will carry with them some power; this power \( P_N \) can be calculated by removing one \( e \) in (2) and replace it with \( eV - E \) which is the energy deposited in the normal metal from one tunneling event. Doing this we obtain [14]

\[ P_N = \frac{1}{e^2 R_N} \int_{-\infty}^{\infty}(eV - E)v(E)(f_N(E - eV) - f_S(E))dE \]

(3)

It is possible for \( P_N \) to be negative and this is the effect we use to cool the normal metal, giving the detector its name.

From energy conservation we conclude that the power dissipated in the superconductor is

\[ P_S = IV - P_N \]

(4)

The responsivity of the CEB in current-bias mode is given by

\[ S_v = -2\frac{\partial I}{\partial V} + G_{e-ph} + 2G_{SIN} \]

(5)

Here \( G_{e-ph} \) is the heat conductance due to electron-phonon coupling and \( G_{SIN} \) is the heat conductance of one tunnel junction [15]. \( \frac{\partial I}{\partial V} \) and \( \frac{\partial I}{\partial T} \) are the partial derivatives of the current with respect to temperature and voltage.

The total NEP of the system can be divided into three parts, the SIN-junction itself, the electron-phonon interaction and also the amplifier noise. The squares of the three parts can be calculated as

\[ NEP_{SIN}^2 = \delta P^2 - 2 \delta P \delta I + \delta I^2 \]

(6)

\[ NEP_{e-ph}^2 = 10k_B\Sigma \Lambda(T_e^5 + T_p^5) \]

(7)

\[ NEP_{amp}^2 = \frac{v_i^2 + N\beta(T_e^5 + T_p^5)}{\beta(T_e^5 + T_p^5)} \]

(8)

In the SIN junction there exist three different sources of noise; \( \delta P^2 \) is the heat flow noise, \( \delta I^2 \) is the fluctuations in the current or shot noise and since the current and the heat flow are correlated there also exists a correlation term \( \delta P\delta I \) [15].

The amplifier contributes two noise sources, \( V_n \) the voltage noise and \( I_n \) the current noise. Assuming \( N \) is the number of bolometers in series and \( W \) is the number of bolometers in parallel, giving a total of \( N \times W \) bolometers, the total NEP is then given by

\[ NEP_{total}^2 = N \times W \times NEP_{SIN}^2 + N \times W \times NEP_{e-ph}^2 + NEP_{amp}^2 \]

(9)

The most optimized combination of these bolometers taking into account the geometry and lowest possible NEP over the full range of incident powers (20 pW to 80 pW, with a margin on both sides of OLIIMPO estimations) is 42 bolometers in series and 2 in parallel. This corresponds to 21 unit cells of the FSS.

The NEP plots for two different power loads calculated from equations 1-6 are shown in Fig. 6. We notice from the plots that the pixel with 42x2 bolometers performs well with NEP of the device less than the photon noise over a range of powers from 20 pW to 80 pW. Thus, the same pixel can be used for both the photometric and spectrometric configurations, whence, in the spectrometer configuration the background power is a lot larger owing to emissions of uncooled spectrometer mirrors.

**D. Fabrication**

The fabrication process is similar to the one described in [18]. The pixel is fabricated using multiple lithography layers. The initial layer consists of alignment marks and defines the pixel size. The next layer is used to expose and evaporate contact pads and the FSS structure. Silicon machining using deep Silicon etch process constitutes the third layer. The Silicon substrate is thinned down to the required thickness using the Bosch process. The Bosch process used for deep silicon etching uses the STS® ICP plasma etcher with SF6 gas in the etch step and CF4 gas in the passivation step providing an
anisotropic etch of the silicon. The process is stopped at the required depth with an etch error typically less than 2 µm. The final layer is the exposure of the CEB devices in an electron beam lithography machine. The size of each of the two bolometer SIN tunnel junctions is 2 µm x 0.4 µm connected with the nanoabsorber being 2 µm long and 100 nm wide and 14 nm thick. After exposure and development of the e-beam resist, the bolometer layers are evaporated. The normal metal absorber is a layer of aluminum whose superconductivity is suppressed by a thin layer of ferromagnetic impurities (Fe). The tunnel barrier of the SIN tunnel junction is formed by oxidation of the normal metal at 10 mbar oxygen pressure for 5 minutes. The superconducting electrodes are then evaporated at two angles (+45° and −45°) to a thickness of 70 nm each. Finally, all unwanted metal and resist is lifted off using warm acetone and a gentle ultrasonic agitation.

E. Prototype testing

The first prototype pixel was fabricated and characterized at low temperatures. The test consisted of measuring voltage response of the device in front of open cryostat windows with room temperature and liquid nitrogen loading. The incoming radiation was filtered with quasioptical bandpass filters along with Fluorogold to decrease infrared power. The optical response to 300 K/77 K loading is shown in Fig. 7. The IV curves of the device are shown on the left axis; the curve with lower linearity corresponds to 300 K radiation. The optical response is plotted on the right axis as the difference in voltage of the two IV curves. This test highlights the optical sensitivity of the device. The power incident on the device with the optical load at 300 K is more than 550 pW and at 77 K is more than 150 pW. Assuming the optical coupling from Fig. 5, the device is operating beyond its designed power load and is overheated. This causes the responsivity to be far lower than at design power loads; here estimated about 4.5 * 10^4 V/W.

For testing the device at lower power loads, a test setup with a cold black body source shown in Fig. 8 was used. The prototype was connected to the 300 mK stage of a cryostat. The sample holder had blackened inner surface to reduce spurious reflections and lowpass and bandpass filters to define the correct optical band. The RF source was a cold black body with a heater and thermometer connected to the 2.7 K stage of the cryostat using a dielectric anchor to prevent heat leaks to the cryostat shields. The incident power on the pixel could be varied by changing the black body temperature between 2.7 K and 6 K.

The incident power could be estimated using Planck’s law. Current-Voltage curves and Voltage-Power curves of the CEB detectors were recorded by changing the black body temperature.

![Fig. 8. The prototype measurement setup](image)

Measurement of the response of the pixel is shown in Fig. 9. The estimated responsivity is also shown in the figure; this is calculated using estimated incident power on the device. The responsivity decreases with increasing incident power which is due to increasing electron temperature of the absorber. In this calculation, the black body emissivity was assumed to be 0.9 and the blackened inner surface of the sample holder is assumed to attenuate any stray radiation falling on it. The fluorogold cover to the sample holder was assumed to have a transmission of unity in the bandwidth of interest.

![Fig. 9. Incident power, optical response and estimated responsivity of the pixel](image)

Another way to estimate the responsivity of the device is by fitting the optical response data to the bolometer model presented in equations 1-5. An IV curve of the device is taken.
with the black body kept at a known temperature. This data is then fitted to the model described earlier and responsivity is calculated. For small changes in radiated power from the black body, this responsivity curve can very reasonably describe the change in absorbed power in the bolometer array. Thus the value of absorbed power can be estimated. Fig. 10 shows data fits to optical response taken at black body temperatures of 2.7 K, 3.6 K and 4.5 K. The two response curves are generated by subtracting individual IV curves at one black body temperature from the lowest one. The data fits indicate that about 0.2 pW of power was absorbed at 3.6 K and about 1 pW power was absorbed by the array at 4.5 K black body temperature. Compared with Fig 9, the estimated absorbed power is lower by about a factor of 2, and the estimated responsivity correspondingly higher. The difference can be attributed to over estimation of emissivity of the black body, under estimation of attenuation of one of the elements in the optical path, difference in the frequency response of the array with the cold stop compared to simulations, or a combination of these instances.

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Using the above estimated responsivity, one can also estimate the electrical NEP by dividing the measured value of noise (at 115 Hz) by the responsivity. This is presented in Fig 11. The background power is estimated to be 6 pW from the data fit and the corresponding photon noise level is indicated. Using the equations 6-9, the calculated NEP for the actual parameters of the fabricated sample is also indicated. The current and voltage noise values are referred to the commercial JFET amplifier AD743 beyond its 1/f corner. This amplifier was used for noise measurement in the actual experiment.

The estimated NEP is about $1.5 \times 10^{-16} \frac{W}{\sqrt{Hz}}$ at optimum bias point and is about 4 times higher than the modelled one. At higher absorbed power, the dynamic resistance of the array will be lower and the impact of the current noise of the JFET amplifier will be reduced. The measurement showed low frequency interferences that were the likely source of the increased noise and of the 6 pW background power indicated earlier. One source of the low frequency interference is the vibrations of the pulse tube cooler of the cryostat used in the experiment. It was not possible to switch it off to reduce its effects since it introduced temperature gradients during the course of the measurement.

To understand the frequency response of the FSS, an experiment was made where the FSS was illuminated with radiation from a Backward Wave Oscillator (BWO) through a bandpass filter chain. Initially the filter chain was characterized separately and then used in the measurements of the FSS. Given the variation of BWO emitted power versus the operating frequency we normalized the measured voltage with the corresponding power reporting the normalized efficiency in the radiation detection. The results are shown in Fig. 12. The filter frequency response has a large enough bandwidth to cover the FSS band. The FSS itself has a frequency response comparable to the simulations shown in Fig. 2.

III. DISCUSSION

Compared to the use of traditional coupling approaches like spider-web bolometer or the slot antennae, the distributed FSS array is conducive to the use of two terminal CEB devices. In
the case of the spider-web or the slot antennae, a single (or few) detector absorbs power that is coupled to the spider-web or through the immersion dielectric lens that usually accompanies the slot antenna. In the case of the FSS array, incident power is distributed over a number of bolometers such that the array of CEBs acts as a distributed absorber along with a distributed coupling element (the FSS geometry). This distribution of power causes each bolometer to be “cooler” which improves the responsivity. In the case of OLIMPO, it was not possible to design a single CEB element that could handle the specified power, so the FSS concept was developed.

The CEB detectors could be used in large-scale arrays, which are needed for almost all future instruments. The device fabrication is not an issue since facilities and competence exists to fabricate arrays over the size of up to 6-inch wafers (> hundred pixels). The most important consideration is the readout system. The multiplexing readout technology for medium/high-impedance sensors is relatively undeveloped. Analog multiplexers based on Si-Ge ASICs could solve the problem [19], by means of low-noise MOSFET switches operating at low temperature with low power dissipation, but this has not been tested with the arrays. Another solution is low-ohmic arrays matched to Superconducting Quantum Interference Device (SQUID) readout. For this goal, well developed SQUID readout systems with multiplexing could be used [20]. For matching of relatively high-Ohmic CEB with low-ohmic SQUID a parallel array of CEBs was proposed for realization of background-limited operation [8]. If impedance matching of the CEB array and SQUID is not enough an additional superconducting transformer could be effectively used for matching.

IV. CONCLUSION

We have designed and fabricated a single pixel of a submillimetre focal plane receiver using Frequency Selective Surface based arrays integrated with the Cold Electron Bolometer detector. Optical response was measured with the cold stop designed for the OLIMPO project and responsivity of $2 \times 10^8 \frac{V}{W}$ was estimated at low power loads and $4.5 \times 10^8 \frac{V}{W}$ at high power loads. Electrical NEP for this array has been estimated to be $1.5 \times 10^{-16} \frac{W}{\sqrt{Hz}}$ at low background power. These results of the prototype testing indicate very promising characteristics of the pixel. We hope to use this approach for future submillimetre focal plane based pixel arrays.

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REFERENCES


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Planar Frequency Selective Bolometric Array at 350 GHz

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Planar Frequency Selective Bolometric Array at 350 GHz

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Abstract—In this paper we describe a bolometric focal plane array consisting of the Cold Electron Bolometer integrated in a Frequency Selective Surface fabricated on a Silicon substrate with a backshort. This array is formed by a periodic pattern of conducting annular square and ring shapes and the two-terminal CEB is embedded directly in the element. The CEBs impedance has been matched to the FSS which provides resonant interaction with incident sub-millimetre radiation. A further degree of freedom for the tuning is via varying the thickness of the substrate. We've been able to design the FSS at 350 GHz with peak coupling of more than 90% as is common for FSS based filters. A prototype of such a detector has been fabricated and optical response to blackbody radiation has been measured, indicating responsivities of $2\times10^4$ V/W and higher at 185 mK and $3\times10^4$ V/W and higher at 300 mK. The details of this new concept, together with numerical simulations and optical measurements are presented.

Index Terms—Cold-Electron Bolometers, planar detector array, frequency selective surfaces, submm wave detectors

I. INTRODUCTION

The concept of Cold Electron Bolometers (CEBs) [1] has been developed and recently brought to the level of potential applications for studies of cosmic microwave background, such as BOOMERanG [2], OLIMPO [3] and LSPE [4]. A CEB embedded into an antenna has high responsivity and a small absorber cross section that reduces its sensitivity to high-energy cosmic rays [5] and makes CEBs advantageous for balloon- and space-borne missions. The CEB consists of a normal absorbing volume coupled to superconducting electrodes via two SIN tunnel junctions. The SIN junction capacitance allows coupling of high frequency currents excited on the antennae (or FSS) to the absorber. The SIN junctions also work as electron coolers which improve the device responsivity and their dynamic impedance can be matched to various readout amplifiers. In the process of designing an array of CEB detectors on a substrate, the problem of substrate modes becomes apparent. In order to get rid of substrate resonances [6], submillimetre planar antennas are either integrated with a quasioptical lens together with the substrate or fabricated on a membrane, whose thickness is less than a quarter of the wavelength. Recently described Lumped Element Kinetic Inductance Detectors (LEKIDs) operate on a $\frac{1}{4}$ wavelength substrate with an antireflection coating [7]. The effective sheet impedance of periodically arranged LEKID stripes is tuned to that of the free space and does not depend on frequency. As a result, substrate modes do not propagate due to strong absorption in the impedance-matched layer of detectors. This concept of a 2D imaging array allows filling of the focal plane of a telescope with a large number of detectors, avoiding the use of quasioptical filters and coupling to incident submillimetre radiation from a wide area determined by the size of Airy spot.

Bolometers due to their nature are sensitive to optical radiation in a wide frequency band. A combination of planar quasioptical filters based on Frequency Selective Surfaces (FSS) is used to narrow down the bandwidth of incident optical power. These filters are based on a periodically repeating elementary pattern (unit cell) that may be based on a great number of shapes like square loops [8] or holes arranged in a honeycomb order [9]. In this work we explore the integration of CEBs into an FSS formed by a periodic 2D array of annular square and ring motif. All the optical power coupled to such an integrated structure is delivered to the bolometers in a narrow frequency band which is determined mostly by the bolometer-free FSS. The imaginary part of the effective surface impedance of the integrated network can be tuned out by the substrate thickness which can be more than quarter (or half) of the wavelength, since the well matched layer of the FSS+CEB array suppresses any substrate modes. A single CEB can handle a finite amount of absorbed power before the electron temperature in absorber increases enough to reduce the responsivity of the device. For handling large power loads typical to balloon-borne missions, an array of CEBs was proposed where incident power could be distributed to keep all bolometers running at lower temperatures [10]. This created a problem of efficiently coupling incident radiation equally to all detectors in the array in a way to avoid the overheating of one (or a few) detectors. Also, the balloon-borne experiments mentioned earlier have been designed to use room temperature JFET amplifiers as readout. The impedance of the CEB array needs to be matched to the noise...

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impedance of these amplifiers. We believe that these problems can be solved by implementing a combination of FSS with an array of CEBs integrated in it.

II. FSS DESIGN

A. FSS and integrated CEB detectors

The Cold Electron Bolometer is a sensitive direct detector with a nonlinear current-voltage characteristic which is dependent on the electron temperature of the normal metal absorber. The CEBs are connected in a series/parallel network to maximize the voltage response to incident power, while at the same time decreasing the total dynamic resistance of the array to match to the noise impedance of JFET amplifiers. We can use the model from [11] to explain the optical response from the series/parallel array.

We begin the design process by choosing a FSS motif that can conveniently integrate one (or more) CEB detector in it. A simple motif is an annular square in the arms of which CEBs can be placed. To couple the detectors to readout, the array of squares need to have coupling lines carrying dc current. Thus the final form of the repeating motif becomes an annular square with lines connecting in one direction. Using a transmission line model described in the next section, estimates are made of the real and imaginary part of impedances offered by the substrate and a backshort. Next, a proper size of the unit cell needs to be chosen. This depends on the Airy spot due to the telescope optics, number of detectors per unit cell, the required imaginary part of impedance that needs to be compensated by the substrate (from estimates) and the total number of detectors that could be used without increasing the pixel NEP beyond the required limit [3]. In our first design a unit cell size of 522 µm x 522 µm is considered which would allow about 30 unit cells in a circular area of 3 mm diameter. These considerations come from the design of a horn coupling the telescope beam to the pixel. This pixel design is created and simulated in the commercial 3D electromagnetic simulator HFSS. The HFSS layout is shown in Fig. 1. The unit cell is illuminated with a Floquet excitation with two orthogonal modes. Periodic boundary conditions are applied to the unit cell to simulate an infinite FSS array.

CEBs are integrated in the arms of the square. The top face of the layout is the backshort.

B. Transmission line model

The schematic of the device is shown in Fig. 2. Since the substrate modes are efficiently absorbed by the FSS layer, it can be described with a simple one dimensional transmission line equivalent circuit diagram as shown. The FSS layer with integrated bolometers serves as an impedance matched absorber for coupling incident electromagnetic radiation together with the substrate and the backshort. The impedance of the substrate is modelled as a transmission line with a finite electrical length corresponding to its thickness in series with the free space impedance of 377 Ω. Similarly, the backshort distance is modelled as a transmission line with an electrical length corresponding to its distance from the FSS. These two impedances are arranged in parallel to the FSS impedance. At resonance, the imaginary part of the FSS surface impedance is tuned out by the substrate and the backshort impedances. Since high frequency currents are excited in the FSS motif, they pass through the matched load (CEB) present in the arms of the motif, cause dissipation of power in the CEB and create a voltage/current response which can then be read out.

Fig. 2. One dimensional transmission line model with values corresponding to a measured sample.

C. FSS Tuning

Using the one dimensional model described above, an estimate can be made of the impedance offered by the substrate and the backshort. Initially, a suitable thickness of substrate and a suitable backshort distance is chosen and their impedance calculated using the equation for the input impedance of a transmission line. The transmission line equivalent corresponding to the backshort length can be considered to be lossless and its impedance is equal to

$$Z_{BSH} = 377*\frac{i}{\tan(k_{BSH}H_{BSH})}$$

(1)

Here, $k_{BSH}$ is the wavenumber in vacuum and $H_{BSH}$ is the distance to the backshort. Similarly, the impedance offered by the combination of substrate and free space is calculated as
\[ Z_{\text{SUB}} = Z_0 \times \frac{377 + Z_0 \times i \times \tan(k_{\text{SUB}} \times H_{\text{SUB}})}{Z_0 + 377 + i \times \tan(k_{\text{SUB}} \times H_{\text{SUB}})} \]  
(2)

\[ Z_0 = \frac{377}{\sqrt{11.7}} \]  
(3)

where \( k_{\text{SUB}} \) and \( H_{\text{SUB}} \) are the wavenumber in the substrate and the substrate thickness. The wave impedance in vacuum is taken to be 377 \( \Omega \) and the relative permittivity of Silicon is assumed to be 11.7 in Eqn. 3.

The impedances are plotted in Fig. 3 for a thickness of Silicon of 140 \( \mu \text{m} \) and distance to the backshort of 160 \( \mu \text{m} \). The imaginary part of the impedance of the substrate is capacitive and dominates that of the backshort. Fig. 4 shows the impedance of the FSS. This can be estimated from simulations by moving the reference plane to the FSS surface thus de-embedding out the substrate. Alternately, one can de-embed the substrate out by removing the parallel substrate impedance component calculated using the transmission line model. The simulations need to be done with the FSS illuminated together with the substrate since the calculation then includes the effect of the near fields excited in the substrate. In this region the transmission line model of the substrate impedance is not valid but since the near field zone is smaller than the thickness of the substrate, the model remains a reasonable approximation.

The FSS performance is simulated using 3D electromagnetic simulation software HFSS. Since the array is designed for sensing arbitrarily polarized radiation we optimized the reflection loss for the two orthogonal linearly polarized modes of the Floquet port. At high frequency the bolometers are equivalent to a lumped element consisting of a 150 Ohm resistor connected in series with a 25 fF capacitor [12]. We represent the 4 embedded CEB detectors with ports of the same impedance as the devices and calculate the scattering parameters of the system. The FSS is represented using a lossy gold metal layer. The return loss for both the Floquet modes is shown in Fig. 5. To calculate the delivered power to the detectors, we use the scattering matrix between the Floquet port and the 4 CEB ports (numbered 2-5). We observe that the loss in the gold lines of the FSS is negligible, and the relation \( \sum_{n=2}^{5} S_{1n}^2 + S_{11}^2 = 1 \) is satisfied, where \( S_{1n} \) is the power coupled to the \( n \)-th detector port from the 1-st mode of the Floquet port \( S_{11} \). Thus, \( S_{11} \) can be used to describe the optical coupling to the detectors while simulating the complete pixel.
The substrate thickness can be used for tuning the resonance frequency of the device. This is possible due to fact that within a reasonable thickness range of the substrate, the impedance is capacitive which can compensate the inductive impedance of the FSS. In Fig. 6, the variation of the resonance frequency with the substrate thickness is simulated and plotted for one of the Floquet modes. It can be noted that spurious resonances are visible higher than the main resonance frequency with very large quality factor. We think that these resonances can be explained by the Wood anomaly found in diffraction gratings [13].

\[ I = \frac{1}{eK_R} \int_{-\infty}^{0} v(E)(f_N(E-eV) - f_S(E))dE \]  

(5)

Here \( e \) is the electron charge, \( R_N \) is the normal resistance of the junction and \( V \) is the voltage across the junction. \( v(E) \) is the Dynes density of states [17] in the superconducting electrode and \( f_s(E) \) is the Fermi-Dirac distribution for the normal metal. \( f_s(E) \) is the Fermi-Dirac distribution of quasiparticles in the the superconductor and in general it will be different from \( f_s(E) \) since they can have different electron temperatures.

The tunneling electrons in the SIN junction will carry with them some power, \( P_N \) can be calculated by removing one \( e \) in (5) and replace it with \( eV-E \) which is the energy deposited in the normal metal from one tunneling event. Doing this we obtain [15]

\[ P_N = \frac{1}{e^2R_N} \int_{-\infty}^{0} (eV-E)v(E)(f_N(E-eV) - f_S(E))dE \]  

(6)

It is possible for \( P_N \) to be negative and this is the electron cooling effect. From energy conservation we conclude that the power dissipated in the superconductor is

\[ P_S = IV - P_N \]  

(7)

The FSS integrated CEBs were fabricated on a silicon substrate. The fabrication process consists of multiple lithography layers. The most important part is the trimming of the Silicon substrate to the required thickness. We use the Bosch Process to thin down the Silicon using SF_6 gas plasma. We stop the plasma process at the required etch depth. The next layer involves the lithography of the gold FSS pattern. The final layer involves the exposure and deposition of the CEB devices. The normal metal absorber is a thin (10 nm) Aluminum film whose superconductivity is suppressed by ferromagnetic impurities (Cr/Fe). The NIS tunnel barrier is created in-situ by oxidation of the Aluminum normal metal. Finally, superconducting Aluminum counter electrodes of about 70 nm thickness each are deposited and unwanted metal is lifted off, similar to [18]. An optical image of a finished sample is shown in Fig. 7. Measured parameters of the fabricated sample were: \( R_s = 1 \) K\( \Omega \)/junction, \( R_a = 150 \) \( \Omega \).

The experimental setup consists of illuminating the sample with blackbody radiation from a cold blackbody source. The
sample together with band defining quasioptical filters is mounted on the mixing chamber of a dilution cryostat. Additional filters to cut off infrared radiation are also mounted on the sample holder. The sample holder faces a cold blackbody mounted on the 2.7 K stage of the cryostat with low thermal conductivity legs to ensure that the blackbody does not heat up other parts of the cryostat by conduction heating. The blackbody temperature can be varied as desired. The CEB array is current biased and commercial JFET amplifiers are used to read out the voltage response of the device. This is shown in Fig. 8.

The blackbody temperature can be varied as desired. The CEB array is current biased and commercial JFET amplifiers are used to read out the voltage response of the device. This is shown in Fig. 8.

The response of the FSS integrated detectors to radiation from a Backward Wave Oscillator (BWO) is shown in Fig. 10. The top panel shows the response of detectors embedded in the square motif and the bottom panel shows the response of detectors embedded in the ring shaped motif. The simulation results for coupling are also shown. The experiment consisted of a BWO radiating through the optical windows of the cryostat through a chopper. A pyroelectric detector measured the BWO power. The optical response and the pyroelectric detector response were measured with lock-in amplifiers. In experiments we observe the effect of multiple reflections inside the cryostat which can appear as discontinuities in the response (especially seen at 330 GHz in Fig. 10 upper panel). We are in the process of optimizing the measurement setup to reduce the effect of such reflections. The peak of the optical response is shifted towards longer wavelengths for the square motif FSS. We believe this is due to etching of the substrate to a larger thickness than intended.

![Fig. 7 – An optical picture of the device fabricated on Silicon substrate. The gold squares and connecting lines can be seen. The bolometers are integrated in the small gaps in the arms of the squares. Size of one arm of the square is about 200 µm while the typical size of the bolometers is about 2 µm.](image1)

![Fig. 8. Voltage response of the array to blackbody radiation plotted against voltage across the array at temperatures shown in the legend. The bath temperature for this measurement was 185 mK. The solid lines indicate data fits using Eqn. 8. The absorbed power is 0.24 pW, 0.5 pW, 1 pW and 1.6 pW from bottom to top. As shown in this figure, a strong voltage response is obtained to radiation from a blackbody heated up to temperatures of 7 K. This data was taken with the bath temperature of 185 mK. Similar experiment was conducted with the bath temperature of 300 mK. The maximum response obtained at these two bath temperatures are plotted in Fig. 9. It can be noticed that the responsivity at 300 mK is about 5-7 times lower than at 185 mK. The estimated responsivity from data fits at 185 mK is greater than $2 \times 10^5$ V/W and about $3 \times 10^8$ V/W at 300 mK.](image2)

![Fig. 9. Comparison of optical response at two different bath temperatures.](image3)

![Fig. 10. Measured response of FSS integrated detectors to radiation from a Backward Wave Oscillator. The solid lines are simulations while the connected diamonds are measurements.](image4)
IV. DISCUSSION

As discussed earlier, the FSS integrated CEB array solution was developed to ensure an efficient distributed coupling system with an array of bolometers. Since the FSS can be designed with any possible repeating motifs, a study was made to compare between different shapes of the motif with regards to the impedance matching properties. Three shapes were chosen – a ring, an annular square described earlier and an annular hexagon. The topologies of the motifs remain the same – an annular shape with two connecting lines for dc bias and 4 bolometers embedded in the arms. The matching chiefly depends on complex part of the impedance of the FSS and the substrate, and how well they can compensate each other. Fig. 11 shows the comparison of the return loss for one of modes of the Floquet excitation. The -3 dB bandwidth for all 3 shapes is comparable, but the ring shape is better when comparing the -10 dB bandwidths. Overall, the choice of shapes depend on the presence (and absence) of possible places for exciting surface resonances [13]. A square and a hexagonal motif have sharp corners that can give rise to such unwanted resonances while a ring shape is free of such “sharp corners.” In general the FSS based detectors have a limited bandwidth between 5%-10% at the frequency of interest. While this can be a limiting factor for some balloon missions, especially LSPE [4] which needs up to 25%, we are working towards increasing the bandwidth of the device. This could involve wider elements or different sized unit cells arranged next to each other but tuned to slightly lower and slightly higher center frequency each.

The measured data was fitted to the CEB model using Eqn. 8 and absorbed power was estimated. The fitting parameters are $\Sigma = 2.1 \times 10^2$ W/µm K$^{-3}$, energy gap of superconductor ($\Delta$) = 195 μeV, $\beta = 0.13$, $P_0 = 5$ fW. It has been shown that the electron phonon decoupling ($T_{e}^2$, $T_{ph}^o$, 5<n<6) increases as the bath temperature is lowered. The value of electron-phonon coupling constant ($\Sigma$) used for fitting is comparable to the one reported in [19] for normal metals fabricated from Aluminum with its superconductivity supressed by ferromagnetic impurities. The high value of $\beta$ is probably due to very small volume of superconducting electrodes in these series of prototypes. Due to power deposited in electrodes ($P_e$), the temperature of quasiparticles in the superconductor increases. This is taken into account while calculating the data fits in Fig. 8 contrary to the classical CEB model [16] where the temperature of quasiparticles in electrodes was assumed to be equal to bath temperature. Quasiparticles in Aluminum have a long lifetime and in a small volume are more liable to interact with phonons and deposit some power back into the normal metal absorber which increases electron temperature in absorber and decreases cooling power.

![Fig. 11. A comparison of three different shapes of the FSS motif – a ring, an annular square and an annular hexagon. The simulations were made for substrate thickness of 140 μm and backshort distance of 160 μm. The bolometer impedance is also kept the same (100 Ω resistance and 25fF capacitance).](image)

V. CONCLUSION

We have designed, fabricated and measured a Cold Electron Bolometer array integrated in a Frequency Selective Surface. We have shown that it is possible to design such an array with unit cell spacing larger than half of the wavelength in the substrate thus decreasing the number of devices required to fill the Airy spot on the focal plane and lowering the NEP. Furthermore, the substrate thickness is shown to tune out the surface impedance of the FSS based array and can also be used as a frequency tuning element. Cryogenic measurements with a cold blackbody show very strong optical response, comparable to previously reported CEB based architectures in this frequency range. We also explored the possibility of using different shaped motifs of the FSS to improve the bandwidth of this device.

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REFERENCES


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A distributed-absorber Cold-Electron Bolometer single pixel at 95 GHz

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A distributed-absorber Cold-Electron Bolometer single pixel at 95 GHz

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We describe a Frequency Selective Surface (FSS) based distributed-absorber Cold-Electron Bolometer (CEB) pixel at 95 GHz integrated in a multi-mode horn. The FSS provides a resonant interaction with incident mm and sub-mm radiation and defines the bandwidth of the array while the horn provides the matching of the beam to the telescope optics. CEB detectors with matched impedance are integrated within the periodic elements of the FSS and generate a voltage response proportional to the incident optical power in the bandwidth of the FSS. A prototype pixel was designed, fabricated and characterized at a temperature of 280 mK. We present optical response to blackbody radiation and fit it to the CEB model. We estimate an optical responsivity of $1.2 \times 10^8 \, \text{V/W}$. A measured bandwidth of 8 GHz of this detector array confirms the frequency selective nature. This prototype represents a good solution for a possible 95 GHz channel of the SWIPE instrument on the LSPE balloon-borne telescope. This kind of multi-mode mm-wave architecture can be easily scaled to other frequency ranges and used on any other balloon-borne telescope focal planes.

I. INTRODUCTION

The measurement of the polarized component of the Cosmic Microwave Background Radiation (CMB) is the main target of several astrophysical experiments observing the sky in the sub-millimeter/far-infrared regime, like ACTpol1, EBeX2, LSPE3, and SPIDER4. This interest comes from the fact that the CMB is a powerful probe for understanding if an inflationary process really occurred during the Planck era. The CMB can also be used for studying several astrophysical observables5 such as galaxy clusters, dark matter and neutrino masses through Sunyaev-Zel’dovich (SZ) effect6. The recent BICEP2 and Planck joined analysis7 demonstrated the compelling necessity of performing polarization measurements of the CMB foregrounds in the frequency bands where the astrophysical emissions dominate over the cosmological signal. The demanding need of detecting these tiny polarized signals, i.e. of the order of fractions of $\mu$K, with photon-noise limited detectors, drives the development of large focal plane arrays able to accommodate thousands of single-mode detectors8, or alternatively hundreds of multi-mode detectors8,9. The multi-mode solution is appealing when high angular resolution is not the driver of the measurement, as in the case of measurements of H-modes in CMB polarization. In this case, a moderate-sized array of multi-moded detectors can collect the same number of modes as a much larger array of single-mode detectors. For photon-noise limited measurements, the survey sensitivity depends on the total number of modes collected by the array, so the same survey sensitivity is obtained with a smaller number of detectors in the case of multi-mode detectors, resulting in a significant simplification of the instrument. In low-background applications, the Noise Equivalent Power (NEP) of multi-moded detectors is dominated by photon-noise while the NEP of single-mode detectors can have a significant additional contribution from intrinsic detector noise. This means that the same final survey sensitivity of a focal plane filled with single-moded detectors can be obtained with a multi-moded detector filled focal plane operating at a higher temperature (eg. 300 mK instead of 100 mK), further simplifying the instrument. We believe that the prototype pixel described in this paper can be a good solution for the 95 GHz channel on the SWIPE10 instrument which is the far infrared polarimeter of the Large Scale Polarization Explorer (LSPE)3.

II. DESIGN

FSS have been well studied and utilized in design of frequency selective bolometers11 with a Transition Edge Sensor fabricated on a thin membrane12. The FSS is a periodic arrangement of repeated metallic elements. Each element has an inductance and a mutual capacitance that exists between neighboring elements. A well designed periodic array can resonate with incident electromagnetic radiation at the frequency of interest. If a detector (say, a CEB) is inserted in such an element then high frequency currents excited due to incident radiation can be coupled to the detector creating an optical response. This is the principle used in the current design.

The unit cell of the pixel is a circular metallic shape with orthogonal slots containing 4 CEBs on a Silicon substrate shunted with a backshort. The unit cell is first

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simulated in the commercial 3D electromagnetic simulator HFSS. A schematic of the unit cell drawn in HFSS software is shown in Fig. 1(a). In the HFSS design the unit cell is illuminated with two orthogonal polarizations of a plane wave. The unit cell has periodic boundary conditions to simulate a periodic array. Initial values of various physical dimensions can be derived using the one dimensional transmission line model described in \(^{13}\). The Silicon substrate thickness and the backshort distance acts as a piece of “transmission line” shunting the periodic FSS structure. By varying the dimensions of substrate thickness and unit cell pitch, the structure is brought to resonance at the frequency of interest (95 GHz). The design thickness of the substrate is larger than the quarter wavelength cutoff at 95 GHz but the well-matched FSS-based pixels efficiently absorb incident radiation and suppress the substrate modes of the bolometric array allowing one to analyze the design using one-dimensional microwave equivalent circuit. The embedded CEB detectors are also simulated in the HFSS design using lumped element properties corresponding to typical CEB resistance and capacitance.

In the fabricated sample, the FSS element pitch is 1055 \(\mu m\), the outer diameter of the FSS ring shown in Fig. 1(a) is 745 \(\mu m\), the inner diameter is 123 \(\mu m\) and the backshort distance is 350 \(\mu m\). The device is fabricated on a high resistivity (>2 k\(\Omega\)cm) intrinsically doped Silicon substrate of thickness 320 \(\mu m\). Alignment marks, FSS elements and contact pads are fabricated in Gold 300 nm thick to decrease RF losses. Using the alignment marks the CEBs are exposed using 100 keV electron beam lithography system. The CEB is a multilayer structure consisting of a non superconducting absorber, a tunnel barrier and a superconducting electrode. The absorber is fabricated from a bilayer of 0.7 nm Iron and 12 nm Aluminum. The tunnel barrier is made by oxidizing the absorber. The superconducting electrode is a layer of Aluminum of thickness 120 nm. Typical dimensions of the absorber of the CEB is 2 \(\mu m\) long and 100 nm wide while the NIS junctions are 2 \(\mu m\) long and 0.5 \(\mu m\) wide.

III. EXPERIMENTAL SETUP

We characterized the spectral response of the sample by illuminating it with a Backward Wave Oscillator (BWO), schematic shown in Fig. 2(a). The sample was cooled down to 280 mK in a testbed cryostat. A back-to-back horn provided optical coupling to incident radiation, while a filter chain (a pair of Fluorogold filters and a pair of custom Neutral Density Filters mounted on the 2.7 K stage of the cryostat) attenuated the thermal radiation from the 300 K background. Problematic reflections from cryostat shields were minimized by the use of RF absorbing foam. Using a chopper tilted 45\(^{\circ}\) with respect to the normal axis of the BWO, the incident radiation was alternatively transmitted to the sample or reflected towards a pyroelectric detector. The spectral response of the sample was synchronously demodulated and normalized against the pyroelectric detector’s response and is reported in Fig. 2(b) and compared with RF simulations. The “noisy” spectral response is most likely due to the residual reflections between cryostat shields.

With mm-wave radiation emitted from a custom blackbody mounted on the 2.7 K stage of our testbed cryostat as shown in Fig. 3(a), we characterized the optical response of the sample. Given the volume constraints inside the cryostat, the LSPE horn was substituted by a smaller one without the backwards flare. In order to decrease the background radiation, the horn aperture was...
set to be a circle with diameter 5 mm. With a 1 kΩ heater the blackbody source was heated in the temperature range (2.7 – 4.2) K and a current-voltage (IV) curve of the CEB array was recorded for each temperature value. Planck’s law was used to estimate the incident power, while the absorbed power was estimated from the CEB model described in Section IV.

IV. ANALYSIS

The measured IV characteristics can be analyzed using the heat balance equation for CEB detectors proposed in\textsuperscript{14,15}. Assume that the CEB array embedded in the FSS consists of \(N\) bolometers in series and \(W\) in parallel from a DC point of view (72 in series and 2 in parallel in this case). \(P_b\) is the background power on the pixel in steady state while \(\delta P\) is the incident signal power. The incident power and the bias current heat up the electron system of the absorber while the tunneling of electrons with energies larger than the Fermi energy of the normal metal across the NIS junction leads to cooling of the electron system. There also exists a heating factor corresponding to the direct Joule heating of the absorber due to the resistance of the absorber \(R_a\) and the bias current \(I\). The heating processes lead to an increase of electron temperature and the cooling processes decrease it. The heat balance can be described as

\[
2P_N + 2\beta P_S - \Sigma A\left(T_e^5 - T_{ph}^5\right) + I^2 R_a + \frac{P_b + \delta P}{NW} = 0
\]  

(1)

Here, \(P_N\) is the power transferred to the normal metal by the bias current. The value of \(P_N\) can be negative indicating electron cooling. \(P_S\) is the power deposited in the superconducting electrode. \(P_N\) and \(P_S\) are described in\textsuperscript{16,17}. \(\beta\) is a parameter which denotes the amount of power returning back from the superconducting electrodes to the normal absorber\textsuperscript{18}. \(\Sigma A\left(T_e^5 - T_{ph}^5\right)\) is the heat lost by the electron system to the phonon system in the absorber, \(\Sigma\) is the electron-phonon coupling constant which is material and temperature dependent, \(A\) is the volume of the normal absorber, \(T_e\) and \(T_{ph}\) are the electron and phonon temperatures respectively. The factor 2 arises due to the two NIS junctions in the CEB.

The response of the bolometric array to the incident power depends on the electron temperature of the absorber and the absorbed power. Due to the nonlinear nature of the NIS IV characteristics, the responsivity is different along different points on the IV curve. This responsivity can be estimated using the expression\textsuperscript{14}

\[
S_V = \frac{\delta V}{\delta P}
\]  

(2)

Using Eq. (1), we have fitted the measured IV characteristics to the CEB model. These fits are shown in Fig. 4(a). The IV curves are scaled in current gain for clarity; the bias current at the point of maximum responsivity is 5 nA. The estimated background power inside the cryostat was 47.2 pW. The value of absorbed power for each IV curve was extracted from the data fits and these power levels are shown in Fig. 4(b) after subtracting the background power on the device. Responsivity of the device estimated using data fitting is shown in Fig. 4(c) and it approaches \(1.2 \times 10^8\) V/W for 61.1 pW absorbed power. It can be observed that the responsivity of the device is dependent on the absorbed power. The astronomical signal is usually a very tiny fraction of the background power load coming from the instrument itself or intervening atmosphere in case of a balloon-borne telescope. Absorption of this tiny signal power does not significantly change the responsivity and Eq. (2) can be used to estimate the signal power from the voltage response. The CEB array is designed to work with JFET amplifiers. The voltage noise\textsuperscript{19} from a JFET cooled to 120 K is about 4 nV Hz\textsuperscript{−1/2}. The NEP of a device is the amount of power corresponding to the measured noise in unit bandwidth. Using a cooled JFET amplifier as the first stage of the readout can bring a readout limited NEP of \(4 \times 10^{-17}\) W Hz\textsuperscript{−1/2} for a background power load of 50 pW using the responsivity values from Fig. 4(c).

V. CONCLUSIONS

We have developed and characterized a prototype 95 GHz planar bolometric array with the Cold-Electron...
bolometers. This design uses the idea of embedding bolometric detectors directly in a Frequency Sensitive Surface in order to create a band limited bolometric detector array eliminating the need of a separate external bandpass filter. The spectral measurements confirm the frequency selective characteristics of the array with an estimated bandwidth of 8 GHz. Optical sensitivity is demonstrated using a blackbody source and resulting data fits indicate a strong optical response with an estimated responsivity of $1.2 \times 10^8$ V/W. This sensitivity is adequate for balloon-borne missions and the impedance of the detectors is compatible with cold JFET readout.

REFERENCES

Power Load and Temperature Dependence of Cold-Electron Bolometer Optical Response at 350 GHz

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Power Load and Temperature Dependence of Cold-Electron Bolometer Optical Response at 350 GHz

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Abstract—Cold-electron bolometers (CEBs) integrated with twin-slot antennas have been designed and fabricated. Optical response was measured at bath temperatures of 0.06 to 3 K using blackbody radiation source at temperatures of 3 to 15 K. The responsivity of $0.3 \times 10^9$ V/W was measured at 2.7-K blackbody temperature that is close to the temperature of the cosmic microwave background. Optical measurements indicate quasi-optical coupling efficiency of up to 60% at low phonon temperature and low signal level. Estimations for bolometer responsivity were made for practical range of bath temperatures and blackbody radiation temperatures. The estimated ultimate dark responsivity at 100-mK bath temperature can approach $S_V = 10^{10}$ V/W and reduces down to $1.1 \times 10^8$ V/W at 300 mK for a device with absorber volume of $5 \times 10^{-20}$ m$^3$.

Index Terms—Cold-electron bolometer (CEB), electron–phonon interaction, superconducting tunnel junctions, twin-slot antennas.

I. INTRODUCTION

Capacitively coupled cold-electron bolometer (CEB) consists of a nanoabsorber and two superconductor–insulator–normal metal (SIN) tunnel junctions connected to planar antenna, schematic view, and scanning electron microscope (SEM) image shown in Fig. 1. In this bolometer, a normal metal strip, thermally isolated from the environment, is heated by incident radiation. The change in temperature is then measured by SIN junctions. The signal power is coupled to the absorber through the capacitance of tunnel junctions, dissipated in the absorber, and removed back from the absorber as hot electrons by the same SIN junctions by the bias current. Electron cooling serves as strong negative electrothermal feedback improving characteristics of the CEB, i.e., time constant, responsivity, and noise-equivalent power (NEP) [1]. Thus, CEB can be a candidate for measuring of cosmic microwave background (CMB) radiation.

For CMB temperature of 2.7 K, frequency of 350 GHz, and bandwidth of 100 GHz, the single-mode power load is 0.1 pW and corresponding photon noise is $7 \text{ aW/Hz}^{1/2}$. Radiation of cosmic dust clouds with temperature up to 30 K produces power loads up to 40 pW corresponding to photon noise of 125 aW/Hz$^{1/2}$. In our previous experiments, we studied series array of 10 CEB bolometers integrated in a cross-slot antenna [2]. In this paper, we integrated CEBs with a twin-slot antenna (see Fig. 2) and measured responsivity in 0.1–30-pW background power range. The double-slot antenna (DSA), also known as twin-slot antenna, is the
most popular type of planar antenna that has been employed in superconductor–insulator–superconductor mixers and hot-electron bolometer mixers [3], [4]. Its spectral and beam pattern characteristics have been studied numerically and experimentally in detail, and its performance is well predicted. Apart from lens coupled slot antenna integrated bolometers, distributed antenna coupled bolometers are an alternative concept for building imaging arrays without lenses or horns for each pixel [5].

II. EXPERIMENTAL RESULTS

Samples with DSA (see Fig. 2) were mounted on an antireflection coated sapphire extended hyperhemispherical lens and irradiated at 350 GHz. For this experiment, a variable temperature blackbody source was fabricated in the form of a flat absorber 25 mm in diameter comprising NiCr film (300 Ω/sq) on a Si substrate. The emissivity of such film is over 90%. The dc or ac current across NiCr film provide changing of blackbody temperature. The blackbody source was also equipped with a temperature sensor connected to the temperature controller. This allowed setting a required temperature in a range between 3 K and 15 K. Due to the small size and proper choice of thermal links, such radiation source has a time constant below 100 ms.

Radiation bandwidth was selected by two bandpass filters placed between the blackbody source and the sapphire lens. Filters were made of thick Cu foil; measured bandwidth is 280–380 GHz with over 20-dB suppression below 280 GHz. Each chip with bolometer structures also contained an array of 100 series-connected SIN thermometers for monitoring of phonon temperature. The sample holder was carefully shielded from stray radiation; wiring is made of twisted pairs thermally anchored on three temperature stages by metal tubes filled with mixture of Stycast epoxy and Cu powder that also serve as RF filter analog to copper powder filters usually used in dilution fridges for RF filtering. A cold container was black painted with Stycast and Bi powder mixture.

Samples with four twin-slot antennas were designed for measuring polarization of incoming radiation. The optimal size of the pixel, according to [6] is $0.5 F \lambda = 0.5 \times 3.5 \times 0.856 = 1.5$ mm, was designed for focal number $F = 3.5$ and wavelength of 0.856 mm. Dimension of each DSA antenna is $240 \mu m \times 150 \mu m$. We measured I–V curves in the bath temperature range of 0.06 K–3 K in dilution microcryostat [7] and from resistance ratio (RR) of SIN junction deduced equivalent electron temperature. Analytic relation for RR is given by [8]

$$\frac{R_d}{R_n} = \sqrt{2kT_e} \frac{\exp \left( \frac{eV_\Delta}{kT_e} \right)}{\pi e V_\Delta \cosh \left( \frac{eV_\Delta}{2kT_e} \right)}.$$  

(1)

Typical dependence values of dynamic resistance on bias voltage for several temperatures around 300 mK are presented in Fig. 3, and RR calculated according to (1) is presented in Fig. 4. One can estimate the electron temperature by measuring RR for zero bias $V_0$, as well as measuring ratio of resistance at bias corresponding to half the superconducting gap to asymptotic resistance $R_{bh}$ in Fig. 4. The latter is more reasonable because response maximum is usually observed around the half-gap voltage across the bolometer. Fig. 3 shows the dynamic resistance from measurements of one DSA sample, which is qualitatively described by relation (1) without noticeable influence of electron cooling and shunting leakage resistance.
Fig. 5. RR and electron temperature $T_e$ dependence values on phonon temperature for dark measurements of DSA sample.

Fig. 6. Radiated power in picowatts and responsivity in microvolts per picowatt dependence values on blackbody temperature.

best obtained RR for dark measurements at 70 mK and zero bias ($V = 0$) approaches $R_d/R_n = 12 000$ that corresponds to electron temperature of 215 mK (see Fig. 5), which is a clear illustration of unavoidable overheating for our bolometers. This overheating could be explained in part by considering the recent evidence from the literature [9], which connects the Dynes density of states of the superconducting electrode to the environmental impact on the tunnel junction (normal metal–insulator–superconductor junction of the CEB in this case). We unavoidably fill the environment of the detectors with high-frequency radiation from the blackbody that could cause the decrease in the dynamic resistance of the tunnel junctions at zero bias, decreasing the RR.

For optical response measurements, we can calculate the incident power using Planck’s formula where $h$ is Planck’s constant, $f_0$ is the central frequency, $df$ is the bandwidth, $k$ is Boltzmann’s constant, $T_R$ is the radiation source temperature, and $\alpha$ is the emissivity.

For the single-mode DSA, antenna power irradiated at the antenna is given by

$$P_{\text{incident}} = \frac{\alpha h f_0 df}{\exp \left( \frac{h f_0}{k R} \right) - 1}.$$  

Absorbed power and corresponding electron temperature of the absorber are presented in Fig. 6. These dependence values were calculated for a signal frequency of 350 GHz, and spectral transmission of bandpass, low-pass, and high-pass filters placed between radiation source and bolometer $df = 100$ GHz. The illumination power value for radiation temperature of 5 K is $P_{\text{ins5K}} = 1 \text{ pW}$.

Dependence values of illuminating power and responsivity on blackbody temperature are presented in Fig. 6. The absorbed power was recalculated from electron temperature of irradiated bolometer according to (3). From the measured I–V curve, we calculate dynamic resistance, compare it with what is expected for ideal SIN junction, and obtain equivalent electron temperature under irradiation. Assuming electron–phonon interaction as the main mechanism of the electron energy relaxation in bolometer

$$P_{\text{ep}} = \Sigma \nu (T_e^5 - T_p^5)$$  

where $\nu = 5 \times 10^{-20} \text{ m}^3$ is the absorber volume for our sample, and $\Sigma = 2 \times 10^7 \text{ W/m}^2\text{K}^{-5}$ is the material parameter taken from [10] and [11] for the similar aluminum film with superconductivity suppressed by ferromagnetic impurities. Thus, we calculate the power absorbed in our bolometer. Ratio of incident and absorbed power corresponds to the optical efficiency of the device.

Earlier, the dependence of responsivity on dc power up to $10^9 \text{ V/W}$ at 100 mK and $10^8 \text{ V/W}$ at 300 mK was measured in [12], and here we present measurements of optical responsivity that is affected by background power load, optical, and impedance mismatches. Theoretical and experimental dependence values of responsivity on radiation temperature are presented in Fig. 7. This dependence is very sharp and shows the importance of reduction for both background power level and phonon temperature. Reducing radiation temperature below 1 K, we still observe overheating at the level of 100 fW, which comes from some background radiation and RF interferences.

We estimate optical efficiency up to 0.6 for low temperature and low signal. To obtain NEP = 30 aW/Hz$^{1/2}$ for such bolometer, the phonon temperature should be below 0.2 K, and the background radiation temperature should be below 2.5 K. For NEP = 2 aW/Hz$^{1/2}$, phonon temperature should be below 0.1 K and background radiation temperature should be below 1.6 K.
III. DISCUSSION

According to [13], the performance of superconductor-insulator–metal–insulator–superconductor (SINIS) bolometer is strongly inverse dependent on electron temperature and absorbed power. The maximum voltage responsivity in the best case at the bias point around the half of the superconducting gap voltage is

$$S_V = \frac{dV}{dP} = \frac{k}{e\sigma T_c^2}. \quad (4)$$

From this equation, we obtain dark responsivity $S_d(100 \text{ mK}) = 10^{10} \text{ V/W}$ and $S_d(300 \text{ mK}) = 1.1 \times 10^8 \text{ V/W}$. The experimental electrical power responsivity of $10^9 \text{ V/W}$ at 100 mK obtained in [12] for dc heating of the absorber corresponds to electrical NEP = 3 aW/Hz$^{1/2}$. Even lower NEP < 0.3 aW/Hz$^{1/2}$ can be successfully measured with superconducting transition-edge nanobolometer at reduced levels of overheating well below 10 fW [14], but the aim of this paper is to estimate the performance of bolometer in realistic conditions of relatively high level of background power load. We can recalculate responsivity dependence on absorbed power as

$$S_V = \frac{k}{e\sigma \nu T_c^2 P^{0.8}}. \quad (5)$$

The calculated responsivity is $S_V = 2 \times 10^8 \text{ V/W}$ at 100 fW and $3.5 \times 10^7 \text{ V/W}$ at 1 pW. These estimations are made for our case of $\Sigma = 2 \times 10^9 \text{ W/(m}^2\text{K}^2\text{)}$ and $\nu = 5 \times 10^{-20} \text{ m}^3$. It means that we can expect NEP$_{bol} = 1 \text{ aW/Hz}^{1/2}$ for our amplifier noise of 10 nV/Hz$^{1/2}$.

Another figure of merit for receiver performance is the level of photon noise given by

$$\text{NEP}_{\text{ph}} = (2 \Phi_{\text{ph}})^{1/2}. \quad (6)$$

For the presented bolometer and experimental setup, the photon noise is not observed due to low level by amplifier noise. If the total noise is reduced down to 1 nV/Hz$^{1/2}$, then photon noise could be observed at absorbed power below 0.4 pW. For single CEB with JFET readout, there is no chance to get photon noise level for power load above 1 pW due to decrease in responsivity and a JFET voltage noise [15].

For background power load of 38 pW, the estimated responsivity is $2 \times 10^6 \text{ V/W}$, NEP$_{bol} = 1 \text{ fW/Hz}^{1/2}$, and the corresponding photon NEP is NEP$_{\text{ph}} = 130 \text{ aW/Hz}^{1/2}$. Hence, observation of photon noise at such power load is not achievable for single bolometer design.

The fundamental limit of thermal energy fluctuations or phonon noise is [13]

$$\text{NEP}_{\text{phonon}} = \left[\frac{10\sigma \nu (T_e^6 + T_{ph}^6)}{1.2} \right]^{1/2} \quad (7)$$

where NEP$_{\text{phonon}} = 0.2 \text{ aW/Hz}^{1/2}$ at 100 mK and 4 aW/Hz$^{1/2}$ at 280 mK, which is well below both photon and bolometer NEPs. Estimations of responsivity and NEP levels for amplifier noise of 10 nV/Hz$^{1/2}$; phonon temperatures of 100, 200, and 300 mK; and power loads of 0.01–38 pW are collected in Table I.

In practical cases, the responsivity is limited by a total power load. With the increase of absorbed power, the responsivity in (5) is reduced as $1/P^{0.5}$. To keep it high, one can try to reduce bolometer volume, but this leads to an increase in electron temperature and finally suppression of response even more. Increase of volume brings less suppression of response but no improvement. Responsivity can be sufficiently increased by using an array of bolometers. In this case, power absorbed in each bolometer is $N$ times less, and responsivity for each bolometer is $N^{-0.8}$ times more; hence, the voltage response for single bolometer is slightly less, but total response of series array is higher. When connected in series for dc, this brings $N$ times more signal; thus, the voltage responsivity for array is

$$S_{\text{var}} = \frac{k_N}{e\nu T_c^2 P^{0.8}}. \quad (8)$$

As example for 280-mK phonon temperature, if we assume that electron temperature should not increase above 300 mK, it corresponds to single bolometer absorbed power of 70 fW. For 1-pW signal, this power should be distributed in 14 bolometers. For 10 pW, it should be 143 bolometers. The limiting factor for increasing the number of bolometers is the phonon power and phonon noise (7); thus, according to [15], the number of bolometers should not be more than

$$N < \frac{P_{\text{ph}}}{\sigma \nu T_c^2 T_{ph}^6}. \quad (9)$$

For measurements of signal above 0.1 pW, we use arrays of bolometers connected in parallel for incoming signal and in series for readout at the output. In a previous work [2], we use ten bolometers for each polarization in a cross-slot antenna. At present, we have three bolometers in a twin-slot antenna. Topologically, it is difficult to fit more than ten bolometers in a planar antenna even at 350 GHz, and for higher frequencies, it is more challenging. Alternative to a single-mode antenna can be a focal plane array of many antennas, but this approach is facing problems of input signal matching and noise mismatch for output amplifier. Parallel connection of bolometers both for input and output with voltage bias and current readout can overcome both of these problems. In this case, a superconducting quantum interference device (SQUID) readout amplifier should be advantageous compared with a convenient JFET room-temperature amplifier.

<table>
<thead>
<tr>
<th>Table I</th>
<th>Estimations of Responsivity and NEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>T, mK,</td>
<td>100</td>
</tr>
<tr>
<td>Power, pW</td>
<td>0.01</td>
</tr>
<tr>
<td>Resp. V/W</td>
<td>$10^3$</td>
</tr>
<tr>
<td>NEP$_{bol}$. W/Hz$^{1/2}$</td>
<td>$10^{-18}$</td>
</tr>
<tr>
<td>NEP$_{\text{ph}}$. W/Hz$^{1/2}$</td>
<td>$2 \times 10^{-18}$</td>
</tr>
</tbody>
</table>
IV. Conclusion

Voltage response of CEB integrated in a DSA has been investigated with respect to phonon temperature and power load. Estimation of dark responsivity up to $10^{10}$ V/W and its decrease below $10^7$ V/W at 5-pW power load corresponds to experimental dependence measured with blackbody signal source at 2 K–15 K radiation temperatures. With amplifier voltage noise of 10 nV/Hz$^{1/2}$, such responsivity corresponds to NEP from 1 to 100 aW/Hz$^{1/2}$. Further improvement of CEB performance can be obtained using focal plane array of planar antennas with single or multiple bolometers in each array element, parallel connection of such bolometers at the output, voltage bias, and SQUID readout. In such configuration, incoming power is divided between antenna array elements with bolometers, which allows preserving high responsivity by decreasing overheating for each bolometer.

REFERENCES


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Valerian S. Edelman was born in 1940. He received the degree from Moscow Physical and Technical Institute, Moscow, Russia, in 1963. He defended the Ph.D. degree in 1968 and the Doctor of Sciences (Habilitation) degree in 1975. Since 1963, he has been with the staff of P. Kapitza Institute for Physical Problems of the Russian Academy of Sciences, Moscow, Russia. The main fields of scientific activity are low-temperature physics, electronic properties of metals and 2-D systems, scanning tunneling microscopy and spectroscopy, and low temperature detectors.

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Paper 5

Optical Response of a Cold-Electron Bolometer Array Integrated in a 345-GHz Cross-Slot Antenna

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Optical Response of a Cold-Electron Bolometer Array Integrated in a 345-GHz Cross-Slot Antenna

Mikhail A. Tarasov, Leonid S. Kuzmin, Valerian S. Edelman, Sumedh Mahashabde, and Paolo de Bernardis

Abstract—Two series/parallel arrays of ten cold-electron bolometers with superconductor–insulator–normal tunnel junctions were integrated in orthogonal ports of a cross-slot antenna. To increase the dynamic range of the receiver, all single bolometers in an array are connected in parallel for the microwave signal by capacitive coupling. To increase the output response, bolometers are connected in series for dc bias. With the measured voltage-to-temperature response of 8.8 µV/mK, absorber volume of 0.08 µm³, and output noise of about 10 nV/Hz¹/², we estimated the dark electrical noise equivalent power (NEP) as NEP = 6 × 10⁻¹⁸ W/Hz¹/². The optical response down to NEP = 2 × 10⁻¹⁷ W/Hz¹/² was measured using a hot/cold load as a radiation source and a sample temperature down to 100 mK. The fluctuation sensitivity to the radiation source temperature is 1.3 × 10⁻⁴ K/Hz¹/². A dynamic range over 43 dB was measured using a backward-wave oscillator, a variable polarization grid attenuator, and cold filters/attenuators.

Index Terms—Bolometer arrays, cold-electron bolometers (CEBs), cross-slot antennas, superconducting integrated circuits.

I. INTRODUCTION

The cold-electron bolometer (CEB) array has been proposed for use as the detector for the 345-GHz channel of BOOMERanG [1]. The requirement is to develop a CEB array with a junction field-effect transistor (JFET) readout for 90 channels. The noise equivalent power (NEP) of the CEB should be lower than photon noise for an optical power load of 5 pW, and polarization resolution should be better than 20 dB for observations of cosmic microwave background (CMB) foregrounds. The radiation power in the CEB is absorbed in a thin normal metal film connected to two superconductor–insulator–normal (SIN) metal tunnel junctions. These SIN junctions serve for electron cooling (similarly to the Peltier effect in semiconductors), and the output signal proportional to the absorbed power is measured on them. Electron cooling makes it possible not only to improve the sensitivity but also to expand the dynamic range due to an increase in the saturation power, because the absorbed power is removed from the absorber by a cooling current [2]. Contrary to heating by dc bias in a hot-electron bolometer, in the CEB, dc bias leads to direct electron cooling. As a result, the noise properties of this device are considerably improved by decreasing the electron temperature. However, for applications in atmospheric radio astronomy such as the BOOMERanG project, the power of microwave background radiation is usually higher than the saturation power of a single bolometer. Our previous theoretical and experimental studies on single CEBs show quite promising NEP down to 2 × 10⁻¹⁸ W/Hz¹/² [3] for dark measurements. Nevertheless, simulations show that it is impossible to satisfy power load requirements of 5 pW with a JFET readout for a single CEB, for both current- and voltage-biased modes. A novel concept of a series/parallel array of CEBs in a current-biased mode has been proposed to effectively match a JFET amplifier readout [4].

The main advantage of the CEB array in comparison with a single CEB is the distribution of incoming power between N CEBs; summing the output signals results in an increased response from the array. An effective distribution of power is achieved by a parallel RF connection of CEBs, which couple to the RF signal through additional capacitance values. The total response is increased because the voltage response of each CEB improves for lower background power, and this is increased by a factor of N in the array configuration, with a corresponding decrease in absorber overheating and saturation. The voltage responsivity in the current-biased mode is

$$S_V = \frac{\partial V_{\text{arr}}}{\partial T_s} \frac{G_{\text{sum}}}{S_{V_{\text{sum}}}}$$

where

$$V_{\text{arr}} = V_{s} \frac{\partial T_s}{\partial T_s}$$

and

$$G_{\text{sum}} = \frac{S_{V_{\text{sum}}}}{S_{V_{\text{sum}}}}$$

are voltages across an array and a single bolometer, respectively; $T_e$ is the electron temperature; and $G_{\text{sum}}$ is the total heat conductance. The amplifier noise related to the array is also proportionally reduced to array responsivity $S_V$. The amplifier impact to NEP NEP_{\text{amp}} = \left( \frac{N \delta V}{S^2} \right)^2 / S_N^2$, where $\delta V$ and $\delta I$ are the voltage and current noise spectral densities, respectively, and $T_e$ is the electron temperature. On the other hand, an increase in $N$ leads to an increase in electron–phonon noise. In our design, we found an optimal number of CEBs, i.e., around ten; in this case, the total noise of the detector becomes less than the photon noise of the incoming signal power load of 5 pW [4].
Fig. 1. Optical image of the cross-slot antenna. Arrays of CEBs are connected to four ports of the antenna. Diagonal slots are capacitive shunted by an additional Al layer deposited above a SiO insulator.

II. EXPERIMENTAL TECHNIQUE

The layout design of a CEB array is optimized for polarizability measurements in a 345-GHz frequency band in order to measure the CMB and foreground polarization with balloon-borne experiment BOOMERanG. Bolometers are integrated in a cross-slot antenna that is placed in the center of a 7 mm × 7 mm chip on an oxidized Si substrate. Antenna design is similar to [5]. Each orthogonal array consists of ten CEBs connected in series for dc bias and readout. A photo of the antenna is presented in Fig. 1. Dark narrow slots are covered with an Al oxide capacitive layer. In each port of the antenna, there are placed five CEBs that are connected in series for each polarization, producing an array of ten CEBs for the vertical and ten CEBs for the horizontal components. The SIN tunnel junctions of the CEBs are made of a CrAl/AlOx/Al trilayer with a nonsuperconducting CrAl bilayer as a normal layer. An advanced shadow-evaporation technique was used for fabrication of the CEB. A detailed view of half of an array with five absorbers and ten tunnel junctions is presented by a SEM image shown in Fig. 2.

Such a chip with the antenna is attached by the back side to an extended hyperhemispheric Si lens with an antireflection coating at 345 GHz. For dynamic range measurements, the lens faces the optical window of the cryostat and is protected against overheating by two low-pass filters (LPFs).

These multimesh filters are produced by QMC Instruments and provide more than 10-dB attenuation above the cutoff frequency of 3 THz for LPF W97s and above 1 THz for LPF B694. The filters were placed at the windows in the radiation shields, at the 70- and 3-K temperature stages. To improve the thermal performance, we placed neutral density filters (NDFs) at the 70- and 3-K temperature stages. To improve the thermal performance, we placed neutral density filters (NDFs) at the windows in the radiation shields, at the 70- and 3-K temperature stages.

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III. DC MEASUREMENT RESULTS

The IV characteristic of an array of ten SINIS CEBs clearly demonstrates the sun gap voltage of 20 SIN junctions. A ratio of dynamic resistance at zero voltage to normal resistance of this array is over 1000, which is close to the theoretical estimation for the operating temperature of 280 mK. We measured the voltage at 0.1 nA bias current as a function of temperature. The maximum measured voltage response to temperature is 8.8 µV/mK. For NEP estimation, we measured the output noise of the array using a MOSFET input instrumentation amplifier (OPA111) as the first amplification stage. For theoretical estimations of the performance of such a bolometer array, we can use the power flow determined by electron–phonon interaction $P = \sum \nu(T - T_0)$ so that $G = dP/dT = 5\sum \nu T^4$. In this case, the responsivity is $S = dV/dP = (dV/dT)/(dT/dP) = (dV/dT)/G$. The volume of the absorber for our array of ten bolometers is $\nu = 10^{-19}$ m$^3$, and the material parameter for aluminium is $\sum = 1.2 \times 10^9$ W · m$^{-3}$ · K$^{-5}$; the thermal conductivity is thus $G = 3.6 \times 10^{-12}$ W/K at 280 mK phonon temperature. Using the measured bolometer output voltage noise ($v_n = 10$ nV/Hz$^{1/2}$ in the white noise region) and the temperature response of $dV/dT = 8.8 \times 10^{-3}$ V/K, we can estimate the minimum dark electrical NEP = $v_n$/$S = 6 \times 10^{-18}$ W/Hz$^{1/2}$. For the actual power load of 5 pW at 345 GHz, the photon contribution to the total NEP can be estimated as $\text{NEP}_{\text{phot}} = (2\eta h f)^{1/2} = 4.8 \times 10^{-17}$ W/Hz$^{1/2}$. It means that our bolometer will operate in a background phonon noise limit.

IV. OPTICAL RESPONSE

We measured the response of this array to the microwave radiation emitted by a cryogenic blackbody radiation source. The radiation source was mounted on the 0.4-K stage; it consists of a constantan foil equipped with a heater and a thermometer. This foil covers the radiation pattern of the antenna and lens. Using
a backward-wave oscillator (BWO) spectrometer/reflectometer, we measured reflection of the foil $R = 0.70 \pm 0.05$ at 345 GHz. This value is different from the zero reflectivity of a blackbody, and the actual emissivity of such source is $κ = 0.30 \pm 0.05$. The response to heating of the emitter is presented in Fig. 3. The measured voltage response to temperature variations of the emitter is 25 $\mu$V/K. Taking into account the emissivity of foil and the root-mean-square (rms) voltage noise 0.38 $\mu$V, we can obtain the temperature sensitivity, which is 5 mK rms. Taking the experimentally measured noise spectra density of the amplifier 10 nV/Hz$^{1/2}$, which dominates in the total noise, we obtain a temperature sensitivity of $1.3 \times 10^{-4}$ K/Hz$^{1/2}$. We can also calculate the power emitted by the heated foil using Planck’s formula for central frequency $f_0 = 345$ GHz and for bandwidth $δf = 100$ GHz of a cross-slot antenna. At a temperature of 3 K, we get

$$\Delta P = \frac{κ \cdot h \cdot f \cdot δf}{\exp(hf/kT) - 1} = 3 \times 10^{-14} \text{ W}$$

where $h = 6.626 \times 10^{-34}$ J $s$ is Planck’s constant, $κ = 1.38 \times 10^{-23}$ J/K is Boltzmann’s constant, $f$ is the frequency, and $κ$ is the emissivity of the radiation source. The voltage response to incoming power is thus $dV/dP = 8 \times 10^{8}$ V/W. For the experimentally measured noise of 10 nV/Hz$^{1/2}$, this corresponds to an optical NEP = $2 \times 10^{-17}$ W/Hz$^{1/2}$. In Fig. 3, we show that the responses of the detector to variations in the power from a thermal radiation source and from a BWO are very similar, whereas the response to changes in the physical temperature of the sample is clearly very different. This difference can be due to suppression of the energy gap due to thermal heating.

Voltage saturation to phonon temperature $V(T_{ph})$ below 200 mK with its derivative $dV/dT_{ph}$ approaching zero at low bath temperatures does not lead to a decrease in optical response $dV/dP$ (see Fig. 4). This means that the electron system is still sensitive to the incoming radiation, and this even makes measurements more stable in the region of saturation to phonon temperature.

Such phonon temperature saturation of voltage can be explained as a balance between electron cooling and overheating due to external radiation and Joule heating via the leakage resistance of tunnel junctions. Estimating the cooling power at 0.1 nA and 1 mV gives $P_{cool} \sim I(V_{\Delta} - V) \sim 10^{-14}$ W. Joule heating for $V = 1$ mV bias and zero-bias resistance that we assume as leak resistance $R_0 = 10 \Omega$ gives $P_{heat} = V^2/R = 10^{-15}$ W. The voltage of saturation for a given current can be obtained from the simple expression $IV_{\Delta} - IV = V^2/R$: we get $V_s = 0.5IR_0[(1 + 4V_{\Delta}/IR_0)^{1/2} - 1] = 1.1$ mV, which is close to the observed value.

V. Dynamic Range Measurements

The effectiveness of connecting bolometers in an array and of electron cooling is illustrated by optical measurements of the dynamic range. For this purpose, we used a BWO that operates in the frequency range 250–380 GHz. A calibrated polarization reflection meter was used for ramping the incident power on the detector. Inside the cryostat, in addition to a cold 20-dB NDF, we also used a cold rotatable stage with a can switch between a 10-dB NDF and an open aperture by an external magnetic field. The measured dependence of the output voltage versus the attenuation of the signal is presented in Fig. 5. Assuming that the weakest detectable signal is determined by amplifier noise (10 nV/Hz$^{1/2}$) and that the strongest is determined by the saturation level, as presented in Fig. 5, at 200 μV, we find that the full dynamic range of this bolometer array is over 43 dB. With a better readout amplifier, this value can increase.

VI. Polarization Sensitivity

We also measured the sensitivity to the polarization degree of the incoming signal by rotating the polarized signal source in front of the optical window. In this experiment, we used a 115-GHz impact ionization avalanche transit time (IMPATT) oscillator and frequency tripler. The voltage dependence of response for polarization angle $φ = 0°, 15°, 30°, 45°, 60°$ is presented in Fig. 6. The maximum response scales as $\sin φ$. 
Fig. 5. Dependence of the output voltage on the attenuation of the incoming signal for the 345-GHz radiation from a BWO. Signal attenuation values for curve B1 are directly taken from the calibrated attenuator. Curve B3 is taken from an additional 10-dB cold attenuator.

Fig. 6. Output voltage dependence on bias voltage for a rotation of the polarized signal source in steps of 15°.

We were not able to measure the ultimate polarization resolution due to vibrations that make instabilities and reflections dominant when the rotation of polarization reduces the signal by more than 10 dB.

VII. CONCLUSION

The CEB array integrated in a cross-slot antenna was measured in a dilution refrigerator with an optical window in the temperature range 0.3–0.1 K. The optical response with NEP = 2 \times 10^{-17} \text{ W/Hz}^{1/2} and fluctuation sensitivity to the radiation source temperature of 1.3 \times 10^{-4} \text{ K/Hz}^{1/2} were measured using a cryogenic blackbody radiation source. The dynamic range over 43 dB and the sensitivity to polarization of the incoming 345-GHz radiation were measured through an optical window using a BWO and an IMPATT diode with frequency tripler. Measured characteristics satisfy requirements for balloon-borne experiment BOOMERanG, and CEBs could be considered for future balloon- and ground-based radio telescope experiments.

REFERENCES


Mikhail A. Tarasov received the degree from M. Lomonosov Moscow State University, Moscow, Russia, in 1977, the Ph.D. degree in 1983, and the Doctor of Sciences (Habilitation) degree in 1997.

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