The space cryogenic submillimeter telescope based on hot-electron microbolometers(Project Submillimetron)

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Abstract

Extremely sensitive detectors are necessary for deep full-sky survey of distant extragalactic sources in the submillimeter-wave region by the cryogenically cooled telescope at the International Space Station (project Submillimetron). Detection of faint sources needs wide-band continuum observation using direct detectors (bolometers) not restricted by the quantum noise of indirect heterodyne receivers. Theoretical considerations and experiments made with laboratory samples of detectors shows that it is possible to realize the necessary sensitivity of 10^{-18} - 10^{-19} W/Hz$^{1/2}$ with antenna-coupled microbolometers at temperature £ 0.1 K. Two types of bolometers are chosen as the most promising ones: normal metal hot-electron bolometer (NHEB) with Andreev mirrors for thermal insulation between absorber and antenna, and NHEB-CC with tunnel junctions for thermal isolation and capacitive coupling of antenna to the absorber. Additional advantages of using such detectors as the base of the project are: high spatial resolution (no undersampling of horn-antenna bolometers), the possibility to operate on wide range of background loads, and direct possibility of polarization measurements.

Introduction

The project of a space cryogenic submillimeter telescope (Project Submillimetron) has been accepted for realization on the Russian Segment of the International Space Station (ISS) [1, 2]. The main goal of the project is a deep full-sky survey in the submillimeter-wave region 0.3-1 THz corresponding to the extraterrestrial background spectrum minimum*, with sensitivity close to the limit of background fluctuations. The project is based on a novel type of hot electron microbolometer, to achieve a sensitivity of approximately 10^{-18} W/Hz$^{1/2}$.

Analysis of detection of the faint distant astrophysical objects has been done, taking into account background influence and effects of sources confusion. The analysis shows that it is possible to detect about 10^6 sky sources by an orbital survey using the existing technology of space cryogenics and optics used in IRAS and ISO missions with telescope aperture of about 0.6 meter. For the following space missions FIRST, PLANK, and IRIS, these results will supply useful initial and/or complementary information.

The novel, highly sensitive microbolometer that we will discuss has been proposed by M. Nahum et al. [3, 4]. It combines planar antenna with a metallic submicron-size absorber and superconductor-insulator-normal metal (SIN) thermal sensor at sub-Kelvin temperatures.

A fundamental difference between bolometers (direct detectors sensitive to radiation power) and heterodyne receivers (linear devices with frequency conversion) is the absence in bolometer noise the limit of "zero quantum fluctuations". A quantum noise limit of bolometer decreases with the decrease of background load. The detection system of Submillimetron project is designed to use this advantage in a extraterrestrial low background condition.

Submillimetron telescope concept

The Submillimetron is a project of the space telescope for astronomical studies at the submillimeter and infrared wavelengths using the facilities of the Russian segment of the ISS. The concept of the Submillimetron telescope includes a 60 cm mirror telescope cooled to liquid helium temperature combined with supersensitive microbolometer arrays. Schematic view of the telescope is shown in Fig. 1.

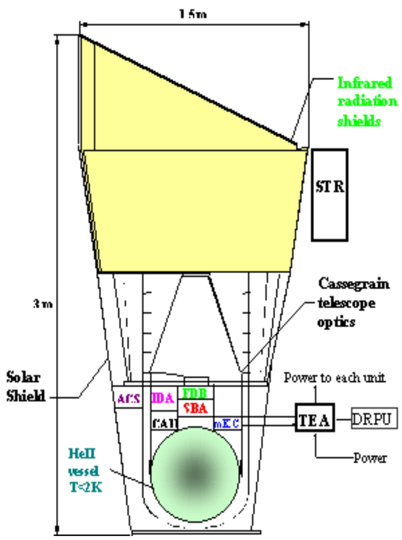


Fig.1

An essential feature of the project is the concept of a free flying instrument with periodic docking to the ISS. Unlike the usual concept of an autonomous mission, this one combines low cost with reliability, refilling, repair and maintenance.

The project was initiated by the Astro Space Center of the P.N. Lebedev Institute after discussions with NASA and Jet Propulsion Laboratory (JPL), supported later by the Russian Academy of Sciences. The proposal was undertaken to perform a feasibility study in the S.P. Korolev Rocket Space Corporation Energia and approved by the Russian Space Agency for the second stage of the ISS construction after years 2004 - 2005.

Detector array concept

Detectors array parameters necessary for the telescope are: wide spectral band Dl/l = 0.1 - 0.3, diffraction-limited angular resolution ~ 1 arcmin, two-dimensional array with number of elements N = 300-1000 for wavelengths 0.3 -0.4 mm. For information about spectrum of detected objects the concept includes additional arrays - linear in infrared bands (N = 100-200) and two-dimensional in long wave bands 0.5, 0.6, 0.8, 1, 1.5 mm (N = 8-300).

The concept of bolometric array was developed on basis of theoretical considerations and laboratory experiments conducted at Chalmers University. It includes NHEB or NHEB-CC type bolometer, voltage-biased SQUID readout, direct electron cooling of the absorber, "dense" array, and "on-chip" frequency selection. The NHEB [5] includes normal metal absorber with thermal isolation from superconducting antenna by means of Andreev reflection and SIN tunnel junctions for temperature measurements. NHEB-CC [6] is capacitively coupled NHEB with thermal isolation by dielectric layer and high-frequency coupling to the antenna by the capacitance of these junctions.

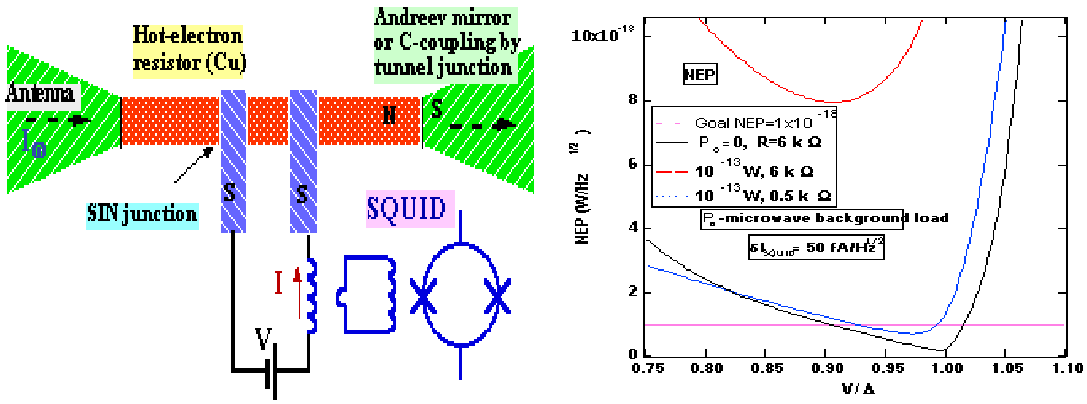
In "dense" array, a distance between elements is less than diffraction spot diameter. It permits "oversampling" of image readout without loss of spatial information in contrast to " undersampling" in existing arrays with horn-antenna coupled bolometers.

The 1 THz sky background varies in a wide range. Thus, an efficient survey program needs detectors that do not saturate at high background and have an extreme sensitivity at low background. In contrast to transition edge sensor (TES), the NHEB bolometers can be optimised for low background sensitivity with only moderate loss of sensitivity at high background level.

The resonant circuit of the capacitance of the NHEB-CC and the inductance of the absorber is the simplest example of "on-chip" frequency selection. More complicated example is the use of strip-line on-chip spectral filters. It does not exclude use of optical blocking filters and dichroic beam-splitters. Measurements of linear polarization are important for astrophysical applications. For bolometers electrically coupled to the antenna (as NHEB) such measurements can be done without additional polarizers.

Bolometer analysis

We analysed the different concepts of the NHEB bolometers theoretically. The analysis shows that the optimal configuration of the bolometer in presence of a realistic background power load is that of the NHEB with voltage-biased SIN tunnel junctions and current readout by a SQUID [7].



[Fig. 2](#)

The total noise equivalent power includes three contributions: NEP_{e-ph} - the noise associated with heat flow between electrons and phonons, NEP_{SIN} - noise associated with the SIN junction, and NEP_{SQUID} – current noise of SQUID equal to 50 fA/Hz$^{1/2}$ in our simulations. The volume of absorber is equal to 0.05 m m^3, which is typical for our experiments. The results are shown for two levels of microwave background power: P_0 = 0 and 10 ^{13} W. The latter figure is a realistic background power load $P_0$for bandwidth 10% at frequencies 300-1000 GHz for background temperature T_{bg} = 3K. The first curve without background load (P_0 = 0) gives NEP = 2x10 $^{-19}$ W for optimal junction resistance 6 k W. Considerable increase of NEP to 8x10^{-18} W is obtained for P_0 = 10^{-13} W. Electron temperature is increased correspondence to the hot-electron formula to 230 mK. Decrease of the R to 0.5 k W leads to increase of efficiency of electronic cooling and returns the NEP to the acceptable level of 8x10^{-19} W and T_e to the level of 100 mK. The goal of NEP for the Submillimetron project is 10^{-18} W [1].

Overheating by the background power load is common for both types of sensors: NHEB and TES using a small absorber. This overheating is dependent only on volume of the absorber (or thermal conductance). However, the NHEB has the great possibility of decreasing the overheating by direct electron cooling to remove all power from the absorber and use it as a useful signal. On the contrary, for normal operation of a TES, an additional dc power $P_{bias} = (P_{signal})_{max}$ should be added to background power that would additionally increase this overheating.

Laboratory experiments

The normal metal hot-electron bolometer ([Fig. 3a](#)) has been made as a prototype of an array element. It is a microscopic power sensor containing a resistive absorber that connects two superconducting antenna terminals (on the ends) and serves as a resistive load for the antenna. A thermometer consisting of two SIN tunnel junctions (at the middle of the strip) reads out the electron temperature. The superconducting electrodes are made of aluminium and the tunnel barrier in the junctions is formed by aluminium oxide.

The electrical power responsivity has been measured by heating the sensor with a small dc current. We have measured the electrical noise-equivalent power NEP = 5 ´ 10 ^{18} W/Hz$^{1/2}$ with a sample cooled to 0.1 K and NEP = 3´ 10 ^{16} W/Hz$^{1/2}$ with a sample at 0.3 K. This corresponds to electrical power responsivity of 4 ´10^{9} V/W and 1 ´ 10^{8} V/W, respectively. The output noise in this experiment was dominated by the room temperature amplifier noise and was in total 22 nV/Hz$^{1/2}$ for f_{meas} = 20 Hz. The NEP data for this experi-ment are shown in Fig. 3b. Theoretical estimations of the NEP for similar parameters of the absorber are shown in Fig. 2.

(a)

(b)

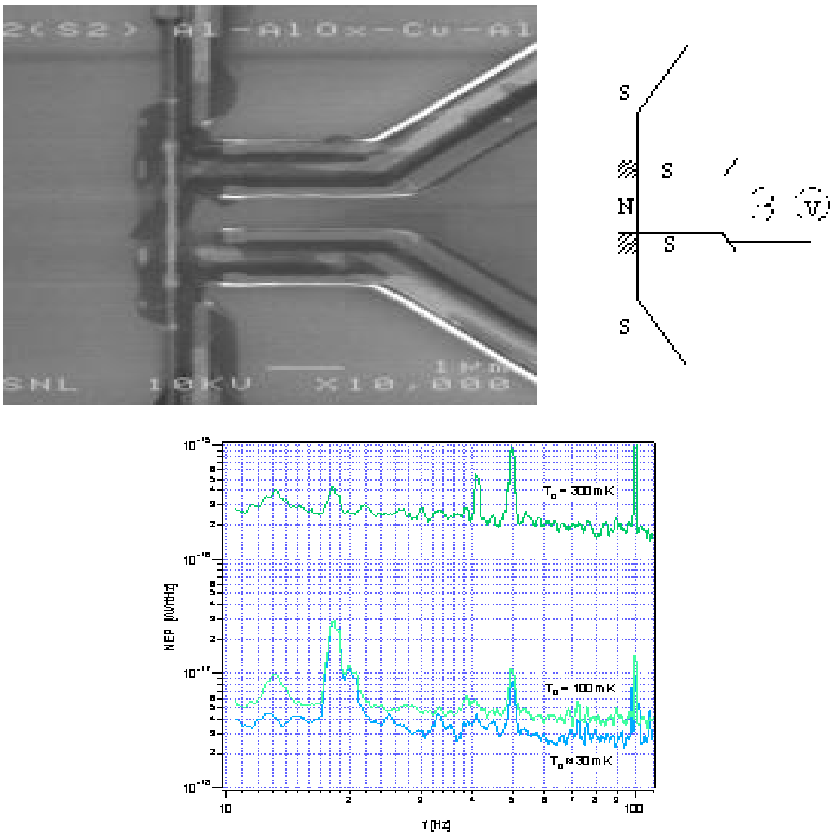


Figure 3. a and b

Our results confirm that from the sensitivity point of view the NHEB can be very attractive as a new detector for space astronomical observations. The measured dependence of the electron temperature in the absorber on the applied heating power is very close to the theoretically expected P = SW $(T^5-T_o^5)$ (where P is the applied heating power, T is the electron temperature measured by the tunnel junction thermometer, T_o is the substrate temperature, W is volume of the absorber film and S is a material parameter of the absorber). This theoretical expression is based on the assumption that the electron-phonon inelastic interaction time depends on T as t µ T^{-3}, and that would correspond to the reaction time of the bolometer close to 10 ^{6} s at 0.3 K.

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The ^{3}He cooler has been manufactured by CEA/DSM/DRFMC, France. The ^{4}He dewar with optical

window has been built by Infrared Laboratories, Inc., AZ, USA.

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* This region is located between peaks of galactic dust emission and extragalactic cosmic microwave background (CMB) measured by the COBE satellite.