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Measurements of dichroic bow-tie antenna arrays with integrated cold-electron bolometers using YBCO oscillators

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Abstract

We consider properties of dichroic antenna arrays on a silicon substrate with integrated cold-electron bolometers to detect radiation at frequencies of 210 and 240 GHz. This frequency range is widely used in cosmic microwave background experiments in space, balloon, and ground-based missions such as BICEP Array, LSPE, LiteBIRD, QUBIC, Simons Observatory, and AliCPT. As a direct radiation detector, we use cold-electron bolometers, which have high sensitivity and a wide operating frequency range, as well as immunity to spurious cosmic rays. Their other advantages are the compact size of the order of a few micrometers and the effect of direct electron cooling, which can improve sensitivity in typical closed-loop cycle ^{3}He cryostats for space applications. We study a novel concept of cold-electron bolometers with two SIN tunnel junctions and one SN contact. The amplitude–frequency characteristics measured with YBCO Josephson Junction oscillators show narrow peaks at 205 GHz for the 210 GHz array and at 225 GHz for the 240 GHz array; the separation of these two frequency bands is clearly visible. The noise equivalent power level at an operating point in the current bias mode is 5×10^{-16} W/√Hz.

Introduction

The cosmic microwave background (CMB) radiation contains a lot of information about origin and evolution of our universe. The temperature and polarization patterns of the CMB give us an accurate picture of the age of the universe and the evolution after the Big Bang [1]. It is currently assumed that the polarization of the CMB radiation can be decomposed into an E mode and a B mode. The more interesting part of the CMB radiation polarization is the B mode. It presumably originates from gravitational waves from the cosmic inflation, while the E mode originates from acoustic waves from the recombination. Currently, the following CMB experiments are in operation or in preparation: Background Imaging of Cosmic Extragalactic Polarization (BICEP) Array [2], Large Scale Polarization Explorer (LSPE) [3], Lite (Light) satellite for the study of B mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD) [4], Q & U Bolometric Interferometer for Cosmology (QUBIC) [5], Simons Observatory [6], and Ali CMB Polarization Telescope (AliCPT) [7].

The BICEP Array is a successor to the Keck Array from the BICEP series. It is a radio telescope installed at the South Pole research station. This telescope is aimed at CMB radiation polarization measurements, in particular, the measurements of the B mode. The Keck Array has been operating since 2012, and work on the BICEP Array was started in 2018. The BICEP Array is planned to observe the polarized microwave sky at 30/40, 95, 150, and 220/270 GHz. It is stated that the 220/270 GHz channel will have more than 20000 detectors. It will use radio frequency (RF) multiplexing with microwave superconducting quantum interference device (SQUID) readout if transition-edge sensors (TESs) detectors are installed. Otherwise, on-wafer RF multiplexing may be used with thermal kinetic inductance detectors [2].

The LSPE mission [3] is a project of the Italian Space Agency aimed at studying the polarization of the B mode of the CMB radiation. The antennas for frequencies of 210 and 240 GHz that we are studying may be used for the Short Wavelength Instrument for the Polarization Explorer (SWIPE) instrument of this project. SWIPE is a radio telescope mounted on a balloon. It has three frequency channels, one main channel at 145 GHz with 30% bandwidth, and two auxiliary channels at 210 GHz with 20% bandwidth and at 240 GHz with 10% bandwidth [3]. It is planned that multimodal TESs with spider-web antennas will be used as detecting elements in the current implementation of this project [8]. These detectors are to be installed into waveguide horns, which is a standard way to form the needed radiation pattern for the antenna. The main channel has 162 detectors, and each of the auxiliary channels has 82 detectors. It is intended to use SQUID readout [9,10] with frequency multiplexing for this mission [8]. The estimated photon noise equivalent power (NEP) for the auxiliary channels is about 2×10^{-16} W/√Hz.

The LiteBIRD is a satellite mission that investigates the B mode polarization of the CMB radiation to test the hypothesis of an expanding universe. This mission is carried out by the Japanese Institute of Cosmonautics and Astronautics with the support of the Japanese Aerospace Exploration Agency. The LiteBIRD payload consists of three telescopes for low, mid, and high frequencies. Mid and high frequencies are treated as a whole. The focal planes of the telescopes are planned to be filled with TES bolometers. The low- and mid-frequency arrays consist of dual- and triple-frequency detectors combined with sinusoidal antennas and silicon lenses. The high-frequency array consists of single- and dual-frequency detectors with orthomodal transducers and silicon horns. This array is aimed at 195, 235, 280, 337, and 402 GHz, and the total number of detectors is 1350. The channels at 195 and 235 GHz each have 254 detectors combined into 127 pixels, and the bandwidth is only 0.3 GHz for each channel. The estimated photon NEP for these channels is about 13×10^{-18} W/√Hz [4].

QUBIC [5] is an instrument for measuring the B mode polarization pattern of the CMB. It is a ground-based experiment planned to be placed in Argentina at Alto Chorrillos in the Santa province. This polarimeter is equipped with bolometric interferometers featuring self-calibration ability for systematic controlling of effects. This feature provides great spectral imaging capabilities to QUBIC. QUBIC is planned to observe the sky at 150 and 220 GHz with 25% bandwidth for both frequency channels. There will be 992 TES detectors for each channel on the focal plane. The estimated NEP for this setup is 4.7×10^{-17} W/√Hz. But because of aliasing in the SQUID readout system and microphonic noise, the NEP in first QUBIC tests was limited to 2×10^{-16} W/√Hz.

The Simons Observatory [6] is a four-telescope ground-based system, including one large-aperture telescope and three small-aperture telescopes. It will be built in Chile in the Atacama desert to study the evolution of the late universe using the Sunyaev–Zeldovich effects. Three frequency bands are used in the Simons Observatory: 30/40, 90/150, and 220/280 GHz. They will be separated by universal focal-plane modules consisting of 432 pixels. It is planned to use TESs as detectors coupled to the optics and microwave-multiplexing SQUID readout. The 220/280 GHz band will have 1728 active detectors and 36 so-called “dark” detectors, used for calibration, per array.

The AliCPT [7] is a ground-based experimental setup aimed at CMB measurements in Tibet, China, at an altitude of more than 5000 m. Tibet is known as one of the best places for CMB observations on the Northern Hemisphere. AliCPT is planned to observe the sky at frequencies of 95 and 150 GHz. AliCPT will use TESs as detectors; there are 1712 of them on a single focal plane, and the total number of detectors will be more than 27000 in the final setup. It is stated that AliCPT will have one of the most sensitive detectors in the world. The total expected NEP of this system is about 6.77×10^{-17} W/√Hz, and the required NEP for this experiment should be below 7.5×10^{-17} W/√Hz.

The concept of arrays of dipole antennas for frequencies of 210 and 240 GHz with cold-electron bolometers, described in the present paper, is proposed to be suitable for such applications. Two arrays placed on a single silicon chip with 7 mm × 7 mm size can independently detect radiation at two frequencies. Here, in the design of dichroic receiving systems, one should overcome the limitation of a silicon substrate, whose thickness affects the efficiency of detection as a refractive medium. In the case of close frequencies, however, one can find a compromise of matching the average frequency of both arrays with reasonable detection efficiency. As a direct radiation detector, we consider using the cold-electron bolometer (CEB) concept [11,12]. These bolometers have high sensitivity with background-limited operation [13-15], a broad operating frequency range, as well as immunity to spurious cosmic rays [16]. Since CEB sizes are of the order of a few micrometers, detector can be placed inside the antenna slot without additional microwave feed lines, forming a multi-absorber array [15,17,18]. Because of this feature, one can adjust the total resistance by forming series or parallel arrays of CEBs to match for either junction field-effect transistor (JFET) or SQUID readout.

The principal advantage of these CEB-based detectors over TESs [19] is the effect of direct electron cooling, when electrons with high energy are removed from a nanoabsorber, leaving only the quasiparticles with low energy and, accordingly, low electron temperature [20-23]. This advantage is important for space, balloon, and ground-based applications. While dilution refrigerators are able to cool down below 50 mK, they cannot operate in extreme or even slightly unstable conditions; even the small variation of a tilt angle can lead to the cryostat malfunction. Typical closed-cycle sorption ^{3}He cryostats, suitable for space and balloon-borne experiments, are limited by their working temperature to about 300 mK. For example, the LSPE-SWIPE custom-designed ^{3}He cryostat cools the two focal planes down to 0.3 K. The ground-based BICEP Array cryostat with a mixed ^{4}He/^{3}He/^{4}He sorption fridge, working at arbitrary elevation angle, is able to achieve a temperature of 250 mK [2]. The AliCPT cooling system is similar to the one of the BICEP array with the same lowest temperature of 250 mK [7]. So, electron cooling is a pathway to improve sensitivity with efficient reduction of electron temperature down to 65 mK from a base temperature of 300 mK [22].

Here we present improved simulation results in comparison with [24] and the first results of fabrication and measurements, using $YBa_2Cu_3O_7$ (YBCO) Josephson junction (JJ) oscillators, of a dichroic multiabsorber receiving system as a prototype for the 210/240 GHz auxiliary channels of the LSPE mission.

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