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GroundBIRD - Observation of CMB polarization with a rapid scanning and MKIDs

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Abstract Cosmic microwave background (CMB) radiation is an afterglow from the Big Bang. CMB contains rich information about the early stage of the universe. In particular, odd-parity patterns (*B*-mode) in the CMB polarization on a large angular scale would provide an evidence of the cosmic inflation. The aim of the GroundBIRD experiment is to observe the *B*-mode on large angular scales from the ground. One of the most novel characteristics of the telescope uses for this experiment is its rapid rotational scanning technique. In addition, the telescope uses cold optics and microwave kinetic inductance detectors (MKIDs). We have developed a telescope mount with a three-axis rotation mechanism (azimuth, elevation, and boresight) and measured the vibration at the focal plane stage a 20 RPM scan rotation rate. We also performed focal plane detector tests on this mount. The tests confirmed the expected response from the geomagnetism associated with the mount rotation. We have also developed a design for the magnetic shields and a detector array on a 3-in wafer. The preparations to begin the observations at the Teide Observatory in the Canary Islands in 2018 are proceeding smoothly.

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1 Introduction

While the Lamda cold dark mater (ΛCDM) model is a standard model that is used to describe the Big Bang universe, there are several subjects that cannot be described using this model, including the horizon problem, the flatness problem, and the monopole overproduction problem in a Grand Unified Theory (GUT) scenario.[1] Cosmic inflation is a novel idea that is intended to resolve these problems. The cosmic microwave background (CMB) contains the cosmic inflation information. In particular, odd-parity patterns in the polarization (B-mode) at large angular scales represent the evidence for cosmic inflation.[2]

In this paper, we report o the development of a three-axis rotation stage for observation applications and the performance of this stage. In addition, we adopted microwave kinetic inductance detectors (MKIDs) for use in the cryostat for the GroundBIRD experiment and measured the responses of these MKIDs to geomagnetic fields. Furthermore, we developed a 120-channel readout system and evaluated its the performance based on measurements of the power spectrum density of the MKIDs in the GroundBIRD cryostat.

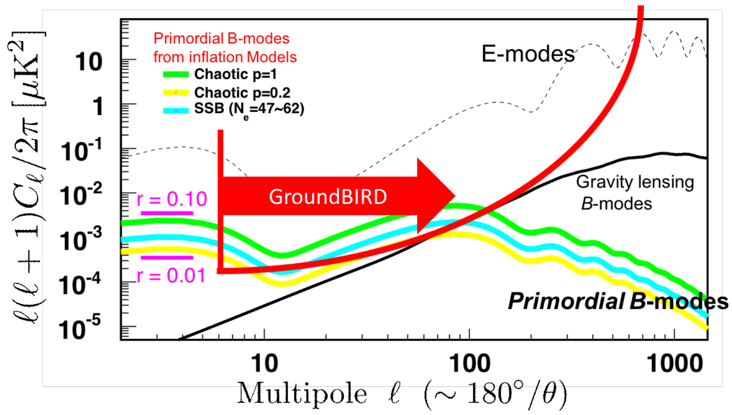

Fig. 1 B-mode spectra predicted using inflation models and the sensitivity of GroundBIRD at a 95% confidence level of GroundBIRD for B-mode detection.[3] r is the tensor-to-scalar ratio that indicates the power of the B-mode. The GroundBIRD experiment is intended to observe large multipole areas ranging from 6 to 300.

2 GroundBIRD Experiment

The GroundBIRD experiment is intended to detect the B-modes on large angular scales from the ground. The target sensitivity for the tensor-to-scalar ratio r is designed to be 0.01 (Fig. 1). To reduce the $1/f$ noise effects, we used the techniques listed below.

– Scan modulation while the whole telescope mount is rotating at 20 RPM,

- Thermal radiation suppression using a cold optics at 4 K,
- Use of MKIDs,

The rapid scanning method is a novel technique in this context and the experiment observes the CMB for the first time when using a rapid scan. The instruments required to realize these techniques are shown in Fig. 2, and our design parameters are listed in Table 1.

Table 1 Design parameters of GroundBIRD

Aperture diameter	300-mm
Optics	Cross-Draone
Beam resolution	0.5-degrees
Field of view	20-degrees
Detector	horn-coupled MKIDs
Frequency band	145 GHz and 220 GHz
Scan speed	120 degrees / sec
observation area	40% of the full sky

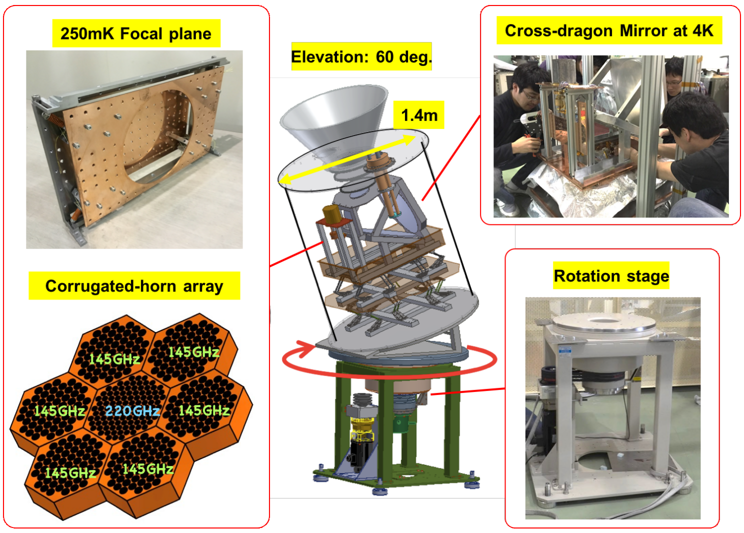

Fig. 2 Overview of the GroundBIRD instrument. We have previously developed other techniques for this instrument, including a rotation stage, a cross-dragon 4 K mirror, and a 120-channel readout system.

2.1 Rapid Rotation Mount for Rapid Scan Modulation

Our telescope is designed to observe CMB over a large field of approximately 20 degrees using with a wide beam ($\theta = 0.5$ degrees). The $1/f$ noise is produced by baseline fluctuations in the detector responses that are generated by the thermal instability of the detector and by atmospheric fluctuations[4,5,6,7]. The typical knee frequency for the $1/f$ noise is approximately 0.1 Hz. One of the most popular and robust techniques used to reduce this effect is modulation by scanning. The general modulation method involves a left-and-right motion at a constant elevation.[8] The rotating scan that is performed in the GroundBIRD telescope can maintain the same speed throughout the entire scan time and is expected to provide the most efficient suppression available. The GroundBIRD telescope rotates along the azimuth direction at 20 RPM. When the telescope elevation is at 60 degrees, the CMB polarization can be measured over a range of multipoles from 6 to 300. We intend to calibrate the baseline fluctuations and preform calibration using sparsely spaced wires (i.e., a wire grid) with an observation configration[9].

2.2 Cold Optics

Because the telescope mirror is not a perfect reflector, it creates an instrumental polarization signal with an intensity that is proportional to the temperature difference between the mirror and the incoming radiation. To reduce the instrumental signal from the mirror, it is necessary for the mirror to be cooled down. We set the telescope mirrors within the 4 K radiation shield and confirmed that the mirror temperature is less the 3.4 K when using the observation configuration.

To provide the required cooling, we used two cooling systems in the GroundBIRD telescope: a pulse tube cryorefrigerator for 4 K cooling and a sorption cooler to reach as low as 250-mK. We installed a 40 K shield, a 4 K shield and 20-layer-thick multi layer insulation (MLI) at the outside of each shield. In the optical path, we used radio-transparent multilayer insulation (RT-MLI[10]) at each shield. The diameter of the optical path is more than 30 cm. In addition, we used a low-pass filter at each radiation shield to delimitate the radiation at the infrared (IR) band. A 350 mK filter was also placed in front of the MKID. We used shedder type of an IR filter, hexagonal high-pass filter, and hexagonal low-pass filter that were selected for each of the frequency bands at the filter stage.

2.3 Detectors

The rapid rotation scanning process requires fast responses from the detector. The response times of the detectors must be less than 0.5 ms. The MKID is advantageous about it offers a response time of approximately 100 μs. Furthermore, hundreds of MKIDs can be readout using only a single feed line. Our MKIDs are the horn-coupled orthomode transducer (OMT) type. The radio-frequency (RF) signal is received by a pair of planar antennas after passing through a corrugated horn array and it then transported to the MKIDs. We adopted a hybrid MKIDs that are composed of a niobium base layer and an aluminum sensitivity layer on a silicon wafer. In the prototype receiver, the typical length of the aluminum part is 2300 um, its width is 4 um, and its thickness is 0.1 um. We fabricated the MKIDs on a 3-in wafer and formed a focal plane using several hexagonal arrays. We intend to adopt two frequency bands: 220 GHz (112 pixels) to acquire a information on dust emission and 145 GHz (330 pixels) to measure the CMB. We only require a single-pair readout cable for each wafer.

Table 2 Design parameters of the MKIDs array

Band GHz	D_{horn} mm	NET $\mathrm{uK}\sqrt{\mathrm{s}}$	Pixel# per wafer	Wafer#	KID#	NET_{array} $\mathrm{uK}\sqrt{\mathrm{s}}$
145	6.3	310	55	6	660	12
220	4.1	530	112	1	224	35

3 Recent Progress

3.1 Magnetic Shield

Because of the rotation of GroundBIRD telescope, the MKID could be sensitive even to the geomagnetism. We have therefore designed a magnetic shield for the GroundBIRD telescope using the ANSYS Maxwell software. The designed shield attenuates the geomagnetic field by approximately -55dB from the exterior at the focal plane.[11]

We studied the effectiveness of the magnetic shielding using an MKIDs array that was installed in a small test cryostat. The detector was cooled to 300 mK and its response was measured with and without the magnetic shield installed at 300 K. We evaluated the function of the shield quantitatively, and we also considered the small uncertainty in the simulation.

We also installed three layers of magnetic shielding sheets (FINEMET MS-FR, Hitachi Ltd.) around the 40 K radiation shield. For the actural observations, we will install a magnetic shield (Amumetal 4K) at the 4 K radiation shield to achieve the -55 dB attenuation.

3.2 Rotation stage

The GroundBIRD telescope uses rapid rotation scanning to observe the CMB. We have developed a rotation stage to transport high pressure He gas. We have also developed a three-axis structure and measured the vibrations at the focal plane duaring observation (Fig. 3). The instability is approximately 0.01 degrees at 20 Hz, which is smaller than the beam size. The offset in the azimuth direction is 0.2 degrees and we plan to calibrate beams by pointing at the observation site.

We measured the responses of the prototype MKIDs array at 2.5-RPM without any magnetic shielding inside of the cryostat. We properly confirmed the response of MKIDs along with the modulation effects of the geomagnetic field. This is the first confirmation that our MKIDs work correctly in the GroundBIRD telescope. Our prospects for mitigation of the geomagnetic field using the shielding are also good, as described in the previous section. We will demonstrate the MKID array after installation of the magnetic shield.

3.3 Readout system

We have developed a readout system for the MKIDs using a dedicated analog board and a commercially available digital board. This readout system is required to retrieve more than 120 tones simultaneously to enable readout of all the MKIDs in a single chip using a single line. We developed a dedicated analog board named “RHEA” that contains two pairs of a 14-bit analog-to-desigal converter (ADC) and a 16-bit digital-to-analog converter (DAC) operating at 200-MSPS.[12] The RHEA board is controlled using the digital board, which is a field-programmable gate array (FPGA) evaluation board (KCU105), and readout operation

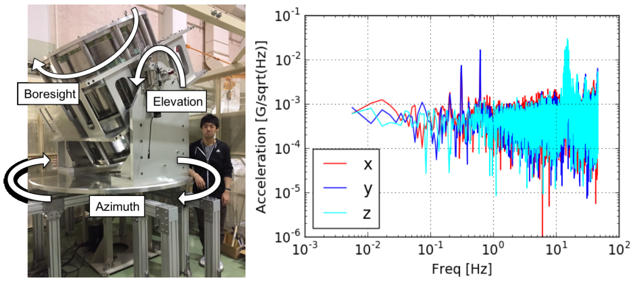

Fig. 3 The GroundBIRD telescope has a three-axis rotation structure (with azimuth rotation, elevation rotation, and boresight rotation). The figure on the right shows the power spectrum density of the vibration with rotation at 20 RPM (X: vertical direction with respect to the focal plane; Y: rotation direction; Z: vertical direction.).

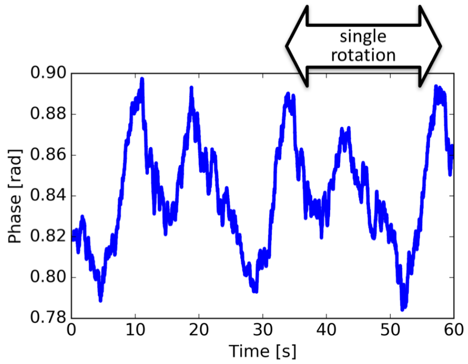

Fig. 4 Time-domain MKID response when the telescope was rotated in the azimuth direction without the magnetic shield.

is possible in various applications. The maximum sampling rate of this system is 1MSPS without any dead time. We implemented a trigger function to detect the response of MKID by a cosmic ray.

3.4 MKIDs

As a prototype device, we developed a small array that contained only 10 MKIDs. We installed this array in the GroundBIRD cryostat and measured its noise spectral density using our readout system. Fig. 5 shows the measured power spectra, which have "roll-off" bumps that are caused by the finite lifetimes of the quasiparticles.[13] We also confirmed that our readout system is usable for the CMB observation. In parallel with this work, we have progressed to fabrications of the full detector array as shown in Fig 6 (Kiuchi et al. LTD17). There are 110 MKIDs on a 3-in wafer that are read out using a single feed line. We will install this array in the GroundBIRD telescope in our future work and will measure the performance of the detector array.

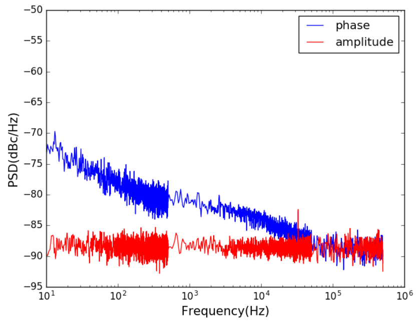

Fig. 5 Power spectrum density of MKID measured using our multi-channel readout system.[14] At the 10^4 Hz, a cut off occurs that is caused by a the lifetime of the quasiparticle.

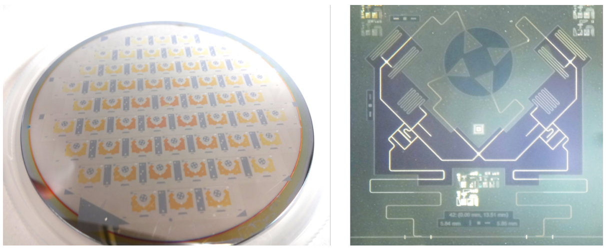

Fig. 6 (Left) Mass production version of the 145 GHz band MKID array. There are 110 MKIDs are contained in a 3-in wafer. (Right) Enlarged view of a single element. The RF signal is transported from the corrugated horn and received at the antenna. After passing through a millimeter wave circuit and the MKID, the response is read out via the feed line (bottom line).

4 Summary

The GroundBIRD experiment is intended to detect the *B*-mode spectrum on large angular scales from the ground. The telescope uses a rapid rotation scanning technique to mitigate the $1/f$ noise effects on the large angular scale (l=6-300). We developed a three-axis structure and cooled the MKID to 300 mK during rotation. In addition, we measured the responses of these MKIDs to the geomagnetic field in the GroundBIRD cryostat during rotation. We have also developed a design for the magnetic shields required for our a detector array, which is contained on a 3-in wafer. We plan to begin the CMB observations in the Canary Islands in 2018.

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