Design of MKID focal plane array for LiteBIRD

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***Abstract*—An MKID focal plane array has been designed for LiteBIRD, which is a future satellite to probe B-mode polarization of cosmic microwave background radiation. Octave-band corrugated horn arrays and planar OMTs are designed for the feed. Three kinds of feed modules detect photons from 55 GHz to 330 GHz with 6 frequency bands. This focal plane array consists of 2780 MKID detectors.**

I. Introduction

LITEBIRD is a future satellite mission for probing B-mode polarization of cosmic microwave background radiation (CMB) to study the cosmological inflation [1]. The science goal of LiteBIRD is to measure the tensor-to-scalar ratio $r = 0.002$, with 2σ sensitivity. It surveys all-sky with linear orthogonal polarization from 55 GHz to 330 GHz with 6 frequency bands (Table 1). Its optics is modified Mizuguchi Dragon reflectors with the aperture diameter of 450 mm and field-of-view (FoV) of ± 15 degrees [2]. LiteBIRD is planned to be launched in the early of 2020th by JAXA.

High sensitivity, high beam qualities, and broadband capability are required for the focal plane array. The detector noise is less than CMB photon noise. The stability or 1/f knee in the noise spectrum is longer than the modulation period of the continuously rotating achromatic halfwave plate [3]. For polarization observations, differential beam shape and differential pointing from the feeds are critical as well as beam shape and cross polarization of each pixel[4]. The TES option of the focal plane array with broadband sinuous antenna and lens has been also proposed for LiteBIRD[5].

II. MKID

Microwave Kinetic Inductance Detector (MKID) is a Cooper-pair breaking photon detector, which consists of superconducting micro-resonators[6]. The resonators with slightly changing their center frequencies ($\sim$ GHz) enable frequency multiplexing. No bias line is required, so many pixels camera is easily realized. Because of a kind of quantum detector using Cooper-pair breaking, MKID is relatively robust over temperature variation and microphonic interferences.

We made antenna-coupled 1/4 wavelength CPW MKIDs similar as the one developed by SRON/TU Delft [7]. The dark noise equivalent power (NEP) has been measured to 5×10^{-18} W/$\sqrt{\text{Hz}}$ [8].

A 600 pixels 220 GHz MKID camera with Si lens array has been developed [9]. Double slot antenna and1/4 wavelength CPW MKIDs with Al 50 nm thickness are patterned on a high resistivity Silicon substrate ($t = 300\mu$m). The Si lens array and mixed-epoxy anti-reflection coating (ARC) have been machined by a high-speed spindle with ceramic endmills in the mechanical engineering shop of NAOJ[10]. The lens diameter and the lens spacing are 1.2λ [11], which is coupled to an F#1 focus [12] .

III. Corrugated Horn Array and planar OMT

Corrugated horns have been widely used for CMB observations and millimeter astronomy due to their excellent beam properties. The near side-lobe level is less than -30 dB and the cross polarization level is less than -30 dB. For polarization observations, differential beam pointing or beam squint is critical. The beam shape of a conical horn is determined by the metal wall, so the differential pointing of dual polarizations coincides in a first order of approximation. On the other hand, differential pointing of the lens coupled antenna is determined by the alignment between the lens and the planar antenna.

Although corrugated horns have some merits compared to lens feeds, there are two demerits: larger fabrication costs of a horn and its narrow bandwidth. Corrugated horn arrays have been developed for a focal plane array with stacked plates [13], [14], [15]. Horn coupled MKIDs have been developed [16], [17].

We designed a broadband corrugated horn as shown in Fig. 1. It has been directly machined from an Aluminum block by the machine shop of NAOJ. The beam pattern was simulated with HFSS and CST softwares. A prototype of this direct machined horn array was confirmed to has a good beam shape and low cross polarization from 120 - 270 GHz.

OMTs have been used for polarization observations. Waveguide OMTs have been developed for ALMA receivers [18], but it was bulky for array detectors. A planar solution for array detectors has been demonstrated by [19], which can also suppress higher modes of a circular waveguide with 180 degree hybrid [20]. Octave bandwidth with a corrugated horn and a planar OMT has been demonstrated for ACT pol[21].

We designed a planar OMT on an SOI (Silicon-on-isulator) wafer for the horn array. The SOI wafer has 6μm thick device layer, 1μm thick SO2 layer, and 400μm thick handle layer. A prototype has been designed to cover frequencies from 80 GHz to 160 GHz and has two frequency bands separated with planar bandpass filters, which will be tested on a ground telescope.

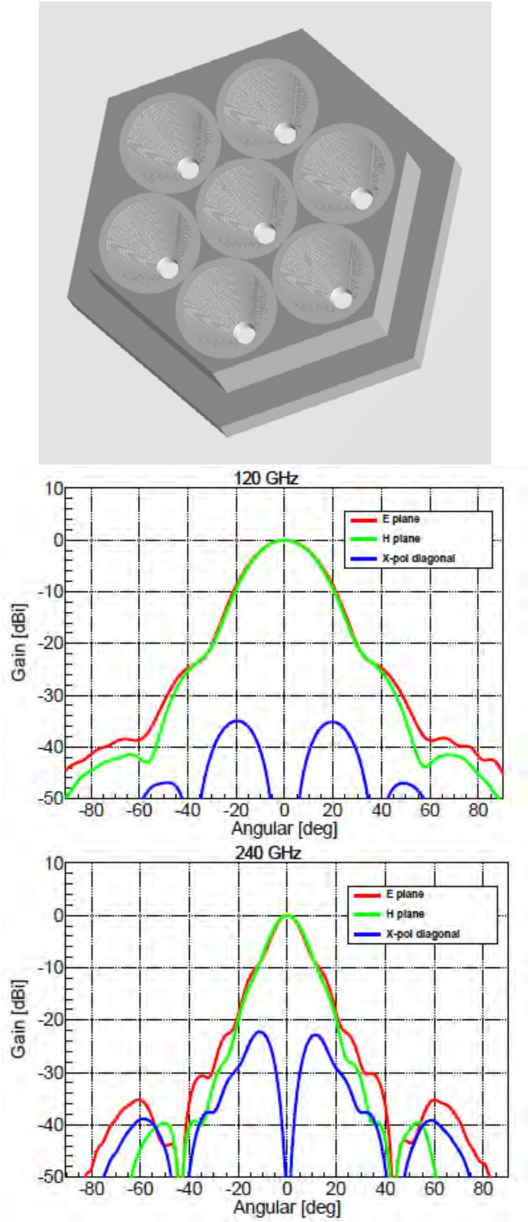

Fig. 1. A schematic drawing of a corrugated horn array and its beam pattern simulation. The horn diameter is 8 mm.

IV. Focal Plane

A focal-plane with MKIDs is designed with corrugated horns as shown in Fig. 2. Each hexagonal module has a diameter of 150 mm. It is optimized to the telecentric focal plane of modified Mizuguchi - Dragon reflectors of LiteBIRD [2]. It consists of three frequency modules as tabulated in Table 1. Each horn has an octave bandwidth and detects two frequency bands with two planar bandpass filters.

The direct machined horn array has several merits. It is possible to reduce stray lights from finite temperature of 4 - 10 K loads of the cold aperture stop and gaps of the reflectors. It also reflects these radiation with emissivity of ~ 0.03, so the radiative heating for this large area is kept to be enough low ($\sim 0.1\mu$ W). Unnecessary parts of the Aluminum horn block are reduced to decrease the weight of the horn array. The Aluminum horn block plays an important role of superconducting electromagnetic shield of MKIDs at 0.1 K.

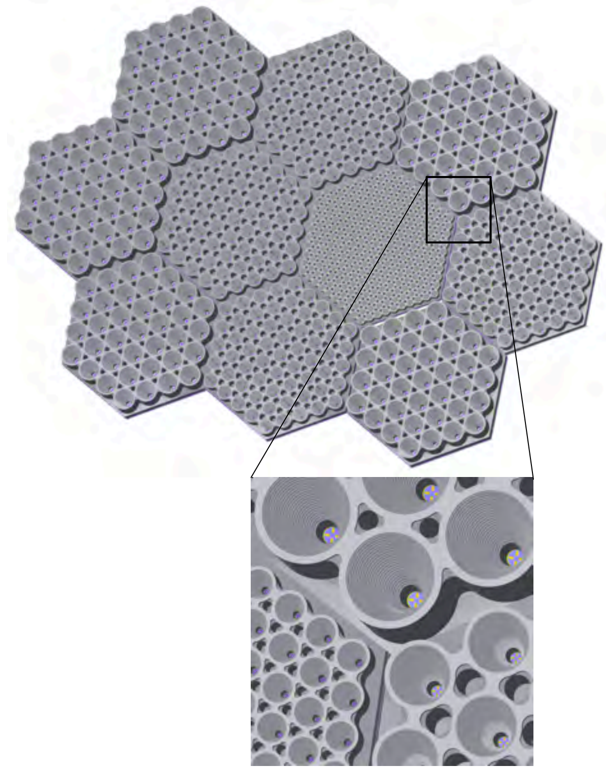

Fig. 2. Conceptional design of an MKID focal plane array with direct machined corrugated horn arrays for LiteBIRD

Schematic diagram of the MKID focal plane is shown in Fig. 3. Ten low noise amplifiers corresponding to each module are installed on the 20 K stage. Coaxial low pass filters (LPF) (eg. [22]) reduce stray lights from warm stages, which may break Cooper pairs.

V. Technical Challenges

There are several technical challenges for this focal plane array. Al-MKID has been already demonstrated to have high performance [23], however, lower frequencies than the gap frequency of 90 GHz has not been demonstrated with NEP around 10^{-18} W/$\sqrt{\mathrm{Hz}}$. MKIDs work at higher frequencies than the gap frequency ν_g which is derived from the transition temperature T_c of a superconductor with the BCS theory.

$$\nu > \nu_g = \frac{2\Delta}{h} = \frac{3.5k_B T_c}{h} = 73[\mathrm{GHz}]\frac{T_c}{1\mathrm{K}}. \quad (1)$$

MKIDs have low NEP at the bath temperature T_b less than $T_c/7$ [8]. With the bath temperature of 100 mK of LiteBIRD,

TABLE I. AN MKID FOCAL PLANE DESIGN OF LITEBIRD.

	Pixel [mm]	Pixel Num	module Num	detector Num	low GHz	high GHz	BW %
Low	24	36	5	360	55	77	33%
				360	78	108	32%
Mid	16	61	4	488	80	113	34%
				488	117	160	31%
High	8	271	1	542	165	227	32%
				542	233	330	34%

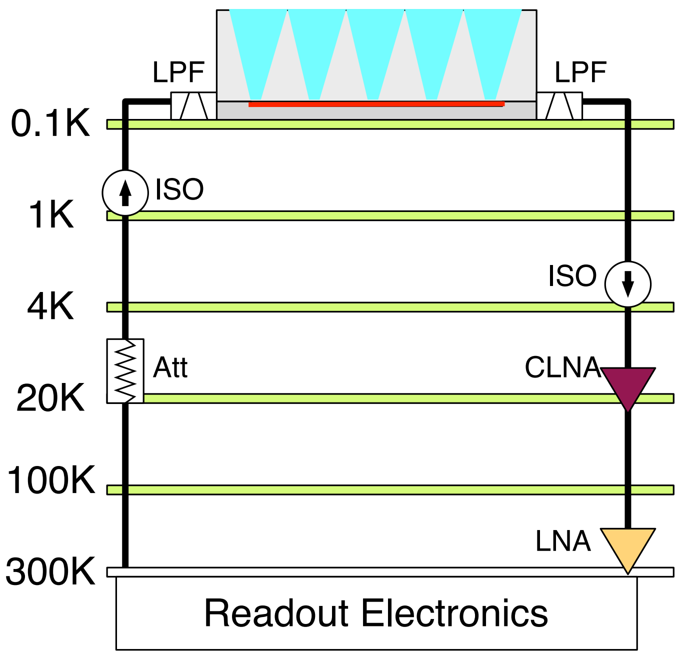

Fig. 3. Block diagram of an MKID focal plane array for LiteBIRD

an appropriate material of $T_c = 700$ mK is required to detect lower frequency bands.

$$\nu_g = 51[\text{GHz}]\frac{T_b}{100\text{mK}}. \quad (2)$$

A promising candidate is a multilayer TiN/Ti/TiN film, where T_c is controlled with layer thickness [17]. It is noted that NEP of TiN film is improved with higher radiation powers[24].

Stability of the detectors or low frequency 1/f noise is also important for CMB observations. Common mode noise of MKIDs can be subtracted. Current baseline design of LiteBIRD uses a rotational half-wave plate [3], which will mitigate this requirement.

High energy particles or cosmic rays in the satellite orbit cause glitches with various time scales in the detector [25]. These events are potential dead time of the detector. Some techniques have to be developed to mitigate them.

ACKNOWLEDGMENT

The authors would like to thank Wenlei Shan, Jochem Baselmans, Akira Endo, Masahiro Sugumito, and LiteBIRD working group for their kind supports. This work was supported by JSPS KAKENHI Grant Number 25247022. TN was supported by a Grant-in-Aid for JSPS Fellows (No. 25001164).

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