Design of a Compact Cold Optics for Millimeter Wave Observations

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Abstract-An optics which we have developed for 220 GHz observations is a compact cold re-imaging one from a telescope focal plane with F/# = 6 to a detector plane with F/# = 1 at 100 mK. It employs two high refractive lenses, high purity alumina (n=3.1) and silicon (n=3.4). To reduce the incident stray light into the detector, a cold nested baffle composed of 4 reflectors with the same spherical shape has been developed. The stray light power is simulated to be 0.2 μ W which corresponds a quarter of that of a without-baffles case. The total transmittance of three kinds of IR blocking filters is 0.78 at the observation frequency, and less than 10^{-10} above 6 THz. Thermal flow power into the detector, including the stray light power, is about 0.7 μ W. The cold optics with an 600 pixels MKID camera has been cooled down to 100 mK.

Index Terms-compact cold optics, high refractive lens, millimeter-wave astronomy

I. INTRODUCTION

W IDE field-of-view (FoV) observation is crucial to survey large area of astronomical sources such as distant galaxies, which helps us to understand the process of galaxy formation [1]. To realize the wide FoV, it is necessary to develop a telescope, focal-plane array detectors, and a re-imaging optics to couple them. One of such wide FoV telescopes is planned [2], and we have been developing aluminum based MKID camera [3]–[5].

In this paper, a re-imaging cold optics which connected with a 600-pixels MKID camera we have developed is demon-

This work was supported by MEXT/JSPS KAKENHI Grant Numbers 21111003, 25247022, 24111712. This work was also supported by a Grantin-Aid for JSPS Fellows (No. 25001164).

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Fig. 1. (a) Ray tracing image of optics calculated with ZEMAX.

strated. For the optics, a refractive optics is adopted because it is more compact than a reflective optics such as SCUBA2 [6] and AzTEC [7]. The requirements is follows;

- 1) To connect a 100 mm diameter F/# = 6 focus of a telescope with a telecentric F/# = 1 focus for the MKID camera. An MKID camera optimized for the F/# = 1focus has a 99% coupling with less than 5 degree tilted beam.
- 2) Reduction of infrared radiation and stray light to cool down the MKID camera. Stray light in the observation frequency becomes a noise source of the detector.
- 3) Total transmittance of IR blocking filters at 200 250 GHz is as high as possible.
- 4) A cold aperture stop exists below 4 K to terminate side lobes of the MKID camera. It also reduces the stray light through the vacuum window into the MKID camera.
- 5) Bath temperature of the MKID camera is kept to less than 150 mK. To satisfy this condition with twice as large as the optical system (a 200 diameter F/# = 6), the thermal loading to this optics is less than 3 μ W.

II. DESIGN

A. Optical design

A refractive optics at 220 GHz with silicon and alumina lenses, which have high refractive indices and low dielectric loss tangents in millimeter wave band [8], was designed. We have developed sub-wavelength structure anti-reflection (AR) coating on the silicon and alumina lenses [8]. Another AR coating using mixed epoxy was also applied for silicon lens

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Fig. 2. Schematic drawing of the compact cold optics.

array coupled with the 600-pixels MKID [8]. A ray tracing image with ZEMAX software [9] is shown in Fig. 1. The beam patterns were calculated and the side lobe level is less than -12 dB at all positions. The Strehl ratio is larger than 95 % at all positions. This optics has 6.6 arcminutes FoV when it is installed in a F/# = 6 focus of a 10 m telescope. It is scalable for wider FoV with larger lenses. It is also planned to install this optics and the MKID camera on Nobeyama 45 m telescope.

B. Mechanical design

A schematic drawing of the refractive cold optics is shown in Fig. 2. Alumina and silicon lenses are mounted at 40 K and 1 K stages, respectively. A cold aperture stop is provided at 1 K. Three kinds of infrared (IR) blocking filters; ZITEX coated PTFE filters [10]; radio-transparent multi-layer insulation (RT-MLI) [11] using Styrofoam 8 layers; and a metal mesh filter [12], are mounted at 300 K, 40 K, 4 K, and 1 K. Transmittance of these filters are measured with a Fourier transform spectrometer (FTS) [13]. ZITEX coated PTFE filter has the cutoff frequency at 6 THz, Styrofoam 8 layers at 1 THz, and metal mash at 300 GHz. The averaged transmittance of superimposed filters is confirmed 0.78 in 200 GHz - 250 GHz and less than 10^{-10} at over 6 THz.

Cold baffles reduce the incident stray light into the MKID camera. A cold nested baffle is mounted at 4 K and three flat baffles are installed at 1 K, 4 K and 40 K, respectively. The nested baffle consists of 4 spherical reflectors with the same radius of curvature (80 mm). They reflect stray light on outside of the baffle. Inside of the nested baffle except for the reflective surface and the flat baffles set 1 K and 4 K are coated with an absorber. The stray light power coming from outside vacuum window into the detector focal plane is 0.2 μ W, which is simulated with LightTools [14]. The baffles reduce 74% stray light power than without-baffles model.

A lens holder has 32 divisions whose structure is similar to a thermal clamp [15]. Divisions of the lens holder play a role in a spring which reduces the pressure applied to lens. 32 divisions lens holders are adopted to reduce applied pressure



Fig. 3. Cooling time of the optical system. Red line shows the detector temperature and it was cooled down to 100 mK.

less than 1/1000 yield stress of the lenses [16]. To reduce magnetic field into the detector, two kinds of magnetic shields, mumetal (A4K) and a superconducting coating, are mounted at 4 K, 1 K, and 100 mK stage, respectively.

These comportents have scalability for twice as large as the optical system.

C. Thermal design

We calculated incident power into 100 mK stage. The thermal sources are radiation, which come from outside of vacuum window including stray light, IR blocking filters, and radiation shields of refrigerator, and conduction from readout cables. The total thermal flow power is 0.7 μ W, which is enough below the refrigerator cooling power.

Optical loading power into one pixel detector is also calculated with assumption of a ground-based telescope at a good observing site, Antarctica [17]. The area of each pixel is assumed with 2.11 mm², which corresponds to a pixel size of the silicon lens array [18]. The total loading power to each pixel of MKID camera is 42 pW. Large loading power is caused at the vacuum window, the styrofoam layers, and the alumina lens.

III. CRYOGENIC EXPERIMENT

All optical components with the 600-pixels MKID camera were installed with the 100 mK dilution refrigerator. The temperatures of all stages were monitored, as shown in Fig. 3. The MKID camera on the focal plane was cooled down to 100 mK in 64 hours whose temperature was consistent with the thermal calculation. High yield of around 95% of the MKID has been achieved. The hot-cold response of the MKIDs was confirmed.

IV. CONCLUSION

A compact refractive cold optics with silicon and alumina lenses has been developed for the 220 GHz band. With a stray light simulation, we confirmed that the with-baffles model decreases 74% incident stray light power compared to the without-baffles model. The 600-pixels MKID camera was cooled down to 100 mK and ~95% yield was achieved. This optical system is scalable for other frequencies and larger FoV. The technology of this cold optics is applicable for a proposed optical system with wide FoV of 1 degree for a 10 m telescope at 850 GHz [19], and a 20,000 pixel MKID camera has been designed for the optical system [3].

ACKNOWLEDGMENT

The authors would like to thank S. Saitou with Advanced Technology Center, National Astronomical Observatory of Japan (NAOJ) for helping in the design of the lens holders and O. Tajima with Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK) for advising on RT-MLI.

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