Development of Direct Machined Silicon Lens Array for Millimeter-wave Kinetic Inductance Detector Camera

Tom Nitta[1,2*], Masato Naruse[3], Yutaro Sekimoto[2], Kenji Mitsui[2], Norio Okada[2], Kenichi Karatsu[2], Masakazu Sekine[2,4], Hiroshi Matsuo[2], Takashi Noguchi[2], Yoshinori Uzawa[2], Masumichi Seta[1], and Naomasa Nakai[1]

[1] *Institute of Physics, University of Tsukuba, Tsukuba, Ibaraki, 305-8577, Japan*
[2] *National Astronomical Observatory of Japan, Mitaka, Tokyo, 181-8588, Japan*
[3] *Graduate School of Science and Engineering, Saitama University, Saitama, Saitama, 338-8570, Japan*
[4] *Department of Astronomy, The University of Tokyo, Bunkyo-ku, Tokyo, 113-0033, Japan*
* Contact: tom.nitta@nao.ac.jp, phone +81-422-34-3942

***Abstract*— We have developed 220 GHz camera using microwave kinetic inductance detectors (MKIDs) for astronomical observations. The optical system of the MKID camera is based on double slot antennas and an extended hemispherical silicon lens array. The diameter of the lens was determined as three times larger than the wavelength at 220 GHz. The 220 GHz camera has 9 pixels. The silicon lens array has been directly machined by high-speed spindle on an ultra-precision machine. The shape fabrication error and the surface roughness of the top of the lens were less than 20 µm (Peak-to-Valley) and about 0.7 µm (rms), respectively. The beam patterns of the MKID camera were measured and are in good agreement with the calculations.**

I. Introduction

Wide field-of-view observations of millimeter-wave and submillimeter-wave emissions are required in order to study star forming regions and distant galaxies which are obscured by dust (for example, [1]). For this purpose, the construction of ground based telescopes such as CCAT [2], and Antarctica Terahertz Telescope [3], as well as the development of large format cameras are planned in the world. Wide-field observations with large format camera play a complementary role with high angular and high frequency resolution observations with the Atacama Large Millimeter/submillimeter Array (ALMA) [4] whose early science observations have just started.

Microwave Kinetic Inductance Detectors (MKIDs) [5] with superconducting microresonators are a promising technology for large format (>1000 pixels) cameras [6]. MKIDs have been widely developed in the millimeter and sub-millimeter wave ranges [7]-[10]. MKID consists of superconducting resonators whose resonance frequencies are distributed in the microwave range, typically 1-12 GHz. Incident photons, which have higher energy than the superconducting gap energy (2Δ), break cooper pairs and create quasi-particles in the resonator. The increase of number of quasi-particles induces a change of the surface impedance of the superconducting film, which decreases the resonance frequency and the quality factor of the resonator. Millimeter and sub-millimeter wave signals are observed by monitoring the shift of the resonance frequency.

The coplanar waveguide (CPW) quarter-wave resonator is well-matched with a planar antenna which is used to couple the signal from the telescope optics to the MKIDs. Most planar antennas require additional focusing elements for efficient coupling to the telescope optics, such as substrate lenses or feed horns. In this study, we adopted the lens array and planar antennas as the optical system for the millimeter wave camera.

II. Lens Design and Fabrication

A. Design of Extended Hemispherical Lenses

The optical system of the MKID camera for the 220 GHz band is based on double slot antennas and an extended hemispherical lens array. The double slot antenna is patterned at the end of the quarter-wave resonator, which is in the opposite side of the feed line. The high-purity polycrystalline silicon (11N purity) was chosen as a suitable lens material because it has small dielectric loss in the millimeter and sub-millimeter bands [11].

The geometrical parameters of the double slot antenna were optimized for a target frequency to minimize return loss (S_{11}) and to achieve symmetrical beam patterns and low side lobe levels. The optimized parameters for the 220 GHz band were 382 µm in length, 25 µm in width and 212 µm in slot separation. The lens diameter is determined as three times of the target wavelength. Here the extension thickness L is defined as L = d - R. Where, d is the distance between the antenna and the top of the lens, and R is the lens radius. In order to determine the extension thickness, the beam patterns of an extended hemispherical silicon lens fed by a double slot antenna were calculated with HFSS, a 3-D full-wave electromagnetic field simulator. Numerical calculations are based on [12]. The extension thickness (L) is optimized considering the beam pattern quality, such as side lobe level and symmetry of main beam. It was determined to be L=0.73

mm for 220 GHz.

B. *Fabrication and Evaluation of the Silicon Lens*

A small diameter lens array has been fabricated with techniques such as photolithography or laser machining [13]-[15]. Ultra-precision cutting by using ball end mills was tried as another efficient technique to process the high-purity polycrystalline silicon in shape of the lens. The 220 GHz lens diameter and the lens spacing were 4.09 mm and 0.3 mm, respectively. To achieve 0.3 mm in lens spacing and get a surface accuracy in the order of μm, a small diameter end mill was needed. In addition, it required a rotating speed of more than several tens of thousands rpm to keep cutting velocity of end mill. Therefore, a combination of the ultra-precise processing machine, Toshiba ULG-300, and the high-speed spindle, Toshiba ABC-20M, is used for this process. The machining tools are made of TiAlN coated ceramic end mill with radius of 0.5 mm and 0.15 mm. Figure 1 shows the photograph of the 9 pixel 220 GHz silicon lens array under processing, and table 1 shows the processing conditions of the silicon lens array.

A three-dimensional coordinate measuring machine was used to measure the shape of the lenses. The shape error from the designed value was less than 20 μm (Peak-to-Valley). The surface roughness of the top of the lens was also measured by using the non-contact three-dimensional measuring machine. The surface roughness of the top of the lens was around 0.7 μm in rms. This value is small enough for use in the millimeter wave range.

TABLE I
PROCESSING CONDITIONS OF THE SILICON LENS ARRAY

Rotating speed	40000 [rpm]
Rotation unbalance	Below 10 [nm]
Cutting feed rate	100-120 [mm/min]
Cutting depth	20-100 [μm]

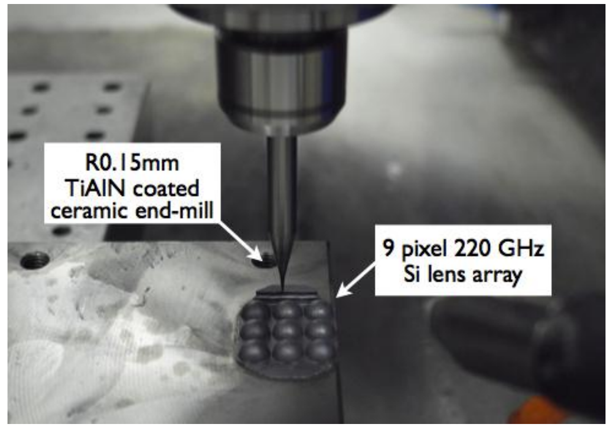

Fig. 1. The photograph of the 9 pixel 220 GHz silicon lens array under processing.

III. Beam Pattern Measurements

A. *Measurement System*

The MKID camera was fabricated by using silicon lens array and Al-based MKIDs. Epitaxial Al(111) film has been grown on a Si(111) wafer by using molecular beam epitaxy [16]. The thickness of the aluminum film was 150 nm. The CPW geometry had a 3 μm-wide central line and 2 μm-wide gaps.

A ^{3}He sorption cooler mounted on a liquid helium cryostat was used for beam pattern measurements of the MKID camera. Temperature of the cold stage was kept at around 300 mK and the holding time is about 8 hours. Figure 2 shows the photograph of the beam pattern measurement system. The millimeter wave signals were radiated from a rectangular probe horn, and scanned around the vacuum window of the cryostat. The response of MKIDs was measured from the S_{21} spectrum taken by a vector network analyzer.

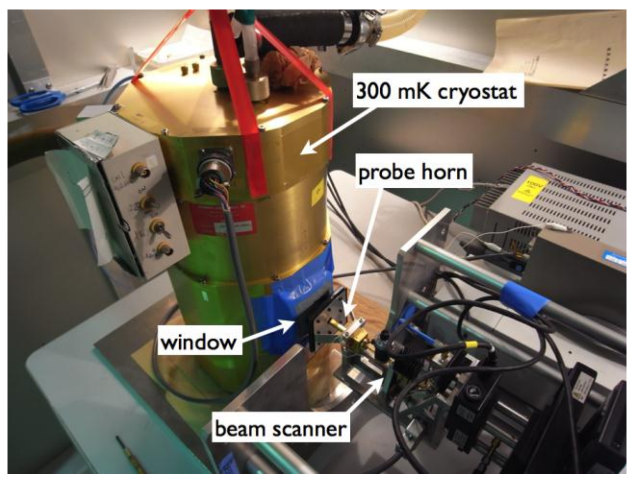

Fig. 2. The photograph of the beam pattern measurement system.

B. *Results*

Figure 3 shows the measurement results of 2D far-field beam pattern of the extended hemispherical silicon lens fed by the double slot antenna at 220 GHz. The dynamic range of this measurement system was about 20 dB, which is limited by the Al MKID's sensitivity at the measurement temperature of 300 mK. The half-power beam width is about 20 degree, and the comparison of the 220 GHz beam pattern between the measurements and the calculations showed good agreement.

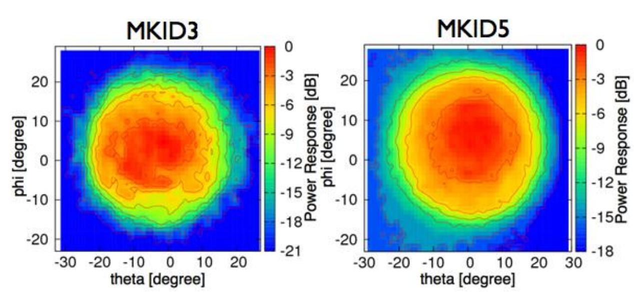

Fig. 3. The measurement results of 2D far-field beam patterns of the extended hemispherical silicon lens array fed by the double slot antennas at 220 GHz. The contours were every 3 dB steps.

IV. Conclusion

In this paper, we reported the development of millimeter wave MKID camera with direct machined silicon lens array, and the measurements of their beam patterns. The silicon lens array has been shaped with ultra-precision cutting techniques, and high-speed spindle. The shape error from the design value and the surface roughness of the top of the lens were less than 20 μm (Peak-to-Valley) and about 0.7 μm (rms), respectively, which shows a good enough processing accuracy for the millimeter wave range. The comparison of the measured beam patterns to the calculations showed good agreement. This proved that the silicon lens array, processed with the ultra-precision cutting, is capable to perform as the optical system of the millimeter wave camera.

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