Development and Commissioning of 100 GHz Microwave Kinetic Inductance Detector (MKID) Camera at the Nobeyama 45 m Telescope

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Abstract – We are developing a resonator-based superconducting camera, microwave kinetic inductance detector (MKID) for application to radio astronomy. MKID has the intrinsic potential to realize over 10000 pixels of the camera because all resonators can be coupled to a single feed line by setting different resonant frequencies. The large number of pixels can realize deep observations in a short time for each astronomical object, as well as wide sky observations in the realistic time duration with a reasonable sensitivity for high-*z* galaxy explorations. A camera with 109 pixels MKID for the 100 GHz frequency band was commissioned at the Nobeyama 45 m telescope in 2018 and 2021 with our own readout system called *FSP*. The detector performances in 2021 commissioning were improved by adopting hybrid-type MKID consisting of NbTiN and Al, while full aluminum MKID were used in 2018. In this article, the overview of our detector, the cryostat receiver, and the data acquisition system are reported with several preliminary results of noise-equivalent flux density by using planet observations.

1. Introduction

Deep observations over the wide sky area are required with millimeter and submillimeter wave ranges to study star-forming regions in the galactic plane, distant galaxy surveys, and cosmic microwave background radiation. To realize both sensitivity and a wide field of view, large pixel array cameras with superconducting detectors were developed. A microwave kinetic inductance detector (MKID) [1] is a resonator of the superconducting film coupled to the antenna, developed as the focal plane detector in the astronomy region. The optical radiation absorbed through the antenna breaks Cooper pairs in the resonator line, which creates two quasiparticles per Cooper pair. By changes in the number of quasiparticles, resonator properties, such as resonant frequency (f_r) and quality factor, are changed. The responsivities of the parameters correspond to the absorbed radiation power in a wide dynamic range. MKID has potential over thousands of pixels coupled to the single readout line with different resonator lengths that can be simultaneously read out by seeing different f_r shifts.

We are developing a 109 pixel MKID camera for the frequency band at 100 GHz. MKID are antenna coupled one-fourth wavelength coplanar waveguide (CPW) resonators on a 3 in silicon substrate. The antenna for each resonator is a double slot antenna coupled to a silicon lenslet of a 5.7 mm diameter with an antireflective (AR) coating. To suppress the physical stress between the silicon lens and the AR coating, the glass beads were attached to the surface of the AR coating. The fabrications of MKID and lens arrays are performed at the Advanced Technology Center (ATC) of the National Astronomical Observatory of Japan (NAOJ) and then evaluated below 100 mK by using the combination of dilution and Gifford-McMahon refrigerators at ATC [2].

Initial 109 pixel MKID were fabricated with aluminum and installed at the Nobeyama 45 m telescope of the Nobeyama Radio Observatory in 2018. The telescope was operated with raster-scanning mode to observe the planets, where the calibration source at ambient temperature was loaded to the cryostat before and after scanning. To cover a wide range of responses from ~300 K to the sky temperature of ~30 K, the readout system called *FSP* was developed with a frequency sweeping scheme, which uses a frequency sweeping probe signal instead of a fixed frequency probe signal [3, 4]. This scheme enables us to simultaneously obtain f_r time-ordered data (TOD) by directly fitting the resonance spectra of MKID. It also has the advantage of the derived resonances not being affected by changes in the gain or delay in the transmission line. Planets were well observed by the

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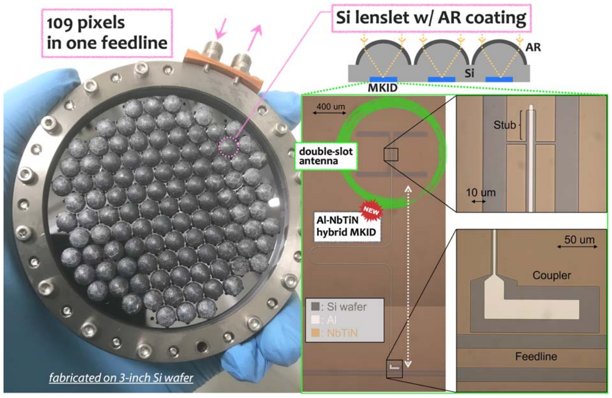

Figure 1. Hybrid NbTiN and Al MKID fabricated at ATC NAOJ. The left picture shows the whole 3 inch detector chip installed in the Nb holder. The silicon lens array wafer can be seen from the front side, while the MKID wafer is attached on the back side. One pair of SMA connectors is attached for simultaneously reading 109 pixel responses. Each lenslet has an AR coating on the surface with glass beads, as shown in the upper right schematics. The bottom right is a photomicrograph of a fabricated MKID. Aluminum is used in the resonator line, while NbTiN is used in the groundplane. All structures were well constructed in the clean room at ATC NAOJ.

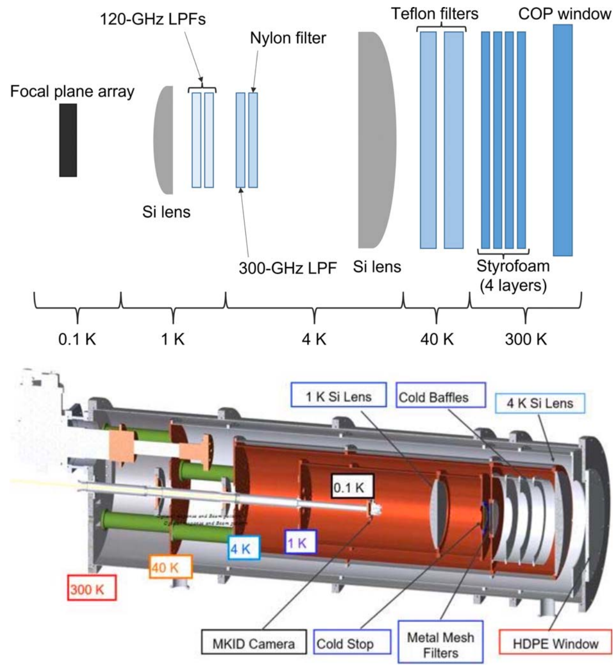

Figure 2. Schematics of cryostat installed at Nobeyama in 2018 [7] and upgraded optical system. Silicon lenses used at 4 K and 1 K thermal shields were upgraded by applying the AR SWS. The vacuum window was also upgraded by changing the material from HDPE to COP with AR SWS. The low-path filters with metal mesh at 1 K also changed the cutoff frequency from 300 GHz to 120 GHz to reduce optical loading.

established observation system with communication protocols with the telescope control [3]. However, the optical efficiency should be improved for better observations by upgrading the MKID and optics of the cryostat receiver.

In this article, the latest on-site performance of the Nobeyama MKID camera system is reported with a summary of developments of MKID pixel arrays fabricated in the ATC clean room and optical system of the cryostat receiver used in the commissioning observations in 2021 and 2022.

2. MKID and Optics Upgrades

To increase the optical efficiency, NbTiN and Al hybrid MKID was used instead of a single metal MKID [5, 6]. Although aluminum was used as the resonator line as with the initial MKID in 2018, NbTiN was fed as the groundplanes on the substrate. The absorbed power with a frequency of 100 GHz did not break Cooper pairs in NbTiN where the gap energy is 1.1 THz (critical temperature $T_c = 14$ K). Therefore, the quasiparticles were generated and trapped in an aluminum line (gap energy of 94 GHz with $T_c = 1.2$ K), which suppressed transmission loss on the resonator by spreading energy to the groundplane. Fabrication parameters were optimized to construct the connection of aluminum and NbTiN at the shorted end and realize narrow antenna geometry on the NbTiN plane. The hybrid MKID chip fabricated in 2020 is summarized in Figure 1.

The optical system of the receiver was upgraded, as well as MKID, to reduce the optical losses on the light pass in the receiver, as shown in Figure 2. By making the AR subwavelength structures (SWS) for Si lenses used at the 4 K and 1 K thermal shields, surface reflections in the 90 GHz to 110 GHz frequency band could be reduced to 1% (30% in bare silicon) [8]. The material of the vacuum window was also changed from high-density polyethylene (HDPE) to a cycloolefin polymer (COP) with AR SWS for higher transmittance. The COP has a similar optic performance as HDPE, but it is easier to add structures on the surface. To reduce the thermal load increased by these improvements, one metal mesh low-path filter at 1 K was replaced to change the cutoff frequency from 300 GHz to 120 GHz. Total filter efficiency was 2.6 times higher than the previous setting in total.

3. Onsite Performance in 2021

After developments of MKID and optics, the receiver was reinstalled with the Nobeyama 45 m telescope at the Nobeyama Radio Observatory, as shown in Figure 3. The cryostat achieved a detector temperature of 82 mK at the observatory ~130 h after the cooling process began, similar to the 2018 observation.

After the detector was cooled down, MKID performances were evaluated. In Figure 3, resonance spectra of NbTiN and Al hybrid 109 pixel MKID are shown. The 103 pixels were successfully detected as the laboratory measurements, where almost the same resonant frequencies were obtained in both the laboratory and observatory, under the room-temperature

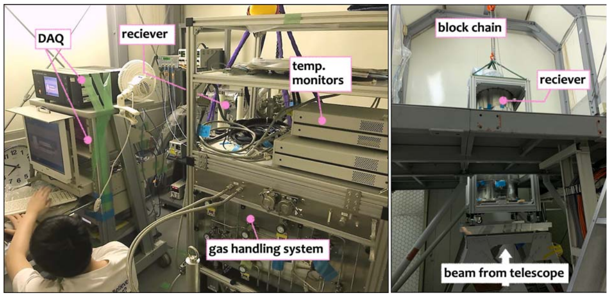

Figure 3. Installation of the MKID 100 GHz receiver to one port of the Nobeyama 45 m telescope. The receiver was installed just above the beam port of the telescope by using a crane and blockchain. In the small space around the receiver, all instruments, such as the data acquisition system, the gas handling system for the dilution refrigerator, and monitors, were installed.

loading condition. The 63 resonant peaks were found to be well separated and used for data analysis in this article as performance evaluation. To see the MKID responsivities, the aluminum mirror was put in front of the receiver window, which reflected thermal radiations from the cryostat inside, providing $\sim$40 K loading to MKID. With higher temperature loading, all resonances were confirmed with the resonant frequencies moving lower and resonance shapes becoming broader and shallower. The noise equivalent power of MKID derived by measurements with $\sim$300 K and 77 K loading was confirmed to be consistent with laboratory measurements.

The planets were scanned as commissioning observations in 2021, as performed in 2018. In this article, the noise-equivalent flux density (NEFD) was evaluated by using Jupiter observation data on June 8, 2021. FSP took the spectrum of each MKID at a 256 Hz sampling rate. By fitting each spectrum, TOD of resonant frequency was obtained, as shown in Figure 5. Noise flux (Jy) was derived from the root mean square of the sky baseline and peak height of Jupiter

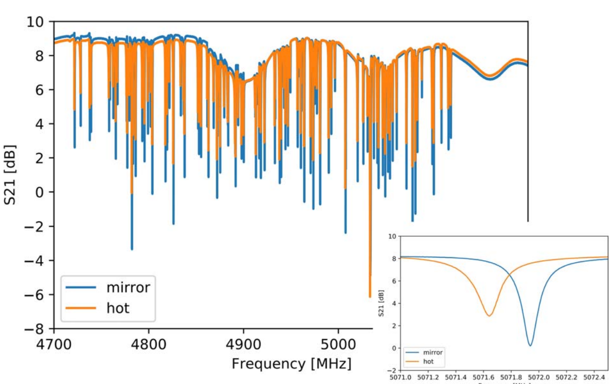

Figure 4. Resonance spectrum of MKID installed in the Nobeyama 45 m telescope. Optical responses to two different temperature loadings were shown with $\sim$300 K black body (orange) and $\sim$40 K by reflecting thermal loading inside the cryostat (blue). The 103 MKID resonance peaks were detected. The bottom right plot shows a well-separated resonator response with different temperature sources.

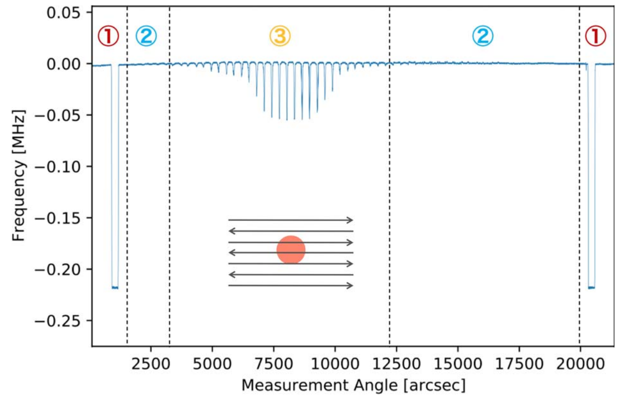

Figure 5. TOD of resonant frequency shifts in a typical MKID pixel. The planet was observed with a raster-scanning mode in a 4 ft $\times$ 4 ft area. The horizontal axis was converted to moving angular distance from time. The observation time was divided into three categories. Before and after observing planets, the calibration source at ambient temperature was illuminated to the receiver, labeled as region 1. The telescope scans the sky with (without) planet peaks in region 2 (region 3).

signal estimated by TOD, with the planet flux given by the model [6]. The NEFD was calculated by dividing noise flux by the square root of the sampling rate. The obtained NEFD is $0.50 \pm 0.16 \mathrm{Jy}/\sqrt{\mathrm{Hz}}$, as shown in Figure 6. In the 2018 observations, NEFD was calculated using Mars observation data on June 1, 2018. Although other parameters, such as beamwidth, were consistent within their uncertainties, NEFD derived in 2018 was found to be $6.00 \pm 2.23 \mathrm{Jy}/\sqrt{\mathrm{Hz}}$, as shown in Figure 6. NEFD are significantly improved by upgrading MKID and receiver optics.

4. Conclusion

In this article, we reported developments of a 100 GHz MKID camera for the Nobeyama 45 m telescope of the Nobeyama Radio Observatory. To achieve the sensitivity improvements, NbTiN and Al hybrid MKID was newly fabricated at ATC NAOJ instead of a single

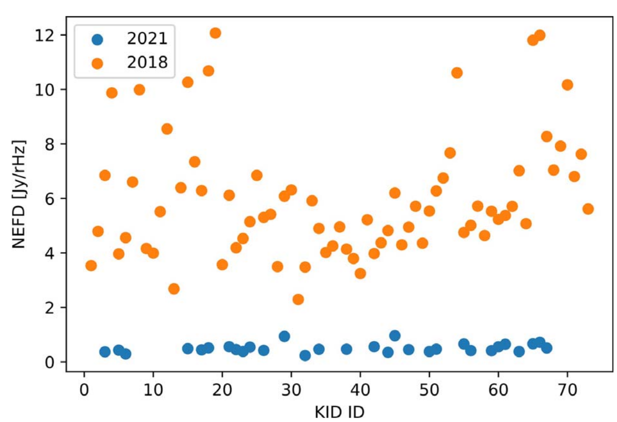

Figure 6. Measured NEFD in each MKID in 2018 and 2021 observations. The NEFD in 2021 are almost one-tenth smaller than in 2018.

aluminum MKID on a 3 in silicon wafer. The optical system was also upgraded by applying AR SWS to the silicon lenses and the vacuum window, which realized 2.6 times higher efficiency with the receiver filters. For the performance evaluation, the NEFD was compared using planet observation data in 2018 and 2021. Due to instrumental upgrades, the NEFD in 2021 is one-tenth smaller than in 2018. NEFD levels are sufficient to observe several star-forming regions and bright quasars. The observations were achieved in 2022, and the results will be reported in the near future. After finishing the observations, the receiver was brought back to the laboratory at ATC NAOJ.

To further improve NEFD down to $\sim 50\mathrm{mJy}/\sqrt{\mathrm{Hz}}$, where MKID are in the photon noise limited condition, the MKID geometrical design should be optimized to reduce $1/f$ noises.

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6. References

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