Complex Beam Mapping of Large MKID Focal Plane Arrays

Kristina K. Davis[1*], Stephen J. C. Yates[2], Willem Jellema[2,3], Ronald Hesper[2], Jochem J. A. Baselmans[4,5], Christopher Groppi[1], Lorenza Ferrari[2], Kotaro Kohno[6], and Andrey Baryshev[2,3]

[1] *School of Earth and Space Exploration, Arizona State University, Tempe, AZ, USA*

[2] *Netherlands Institute for Space Research, Groningen, NL*

[3] *Kapteyn Institute, University of Groningen, Groniningen, NL*

[4] *Netherlands Institute for Space Research, Utrecht, NL*

[5] *Terahertz Sensing Group, Delft University, Delft, NL*

[6] *Institute for Astronomy and Research Centre for the Early Universe, University of Tokyo,Tokyo, JP*

*Contact: Kristina.davis.1@asu.edu

Abstract—Complex radiation pattern measurements of cameras for astronomical observatories are advantageous over total power radiation pattern measurements because of the wider range of analysis they allow. Probing both the amplitude and phase structure of the camera allows direct comparison between the measured field and electromagnetic simulation data, and allows propagation from the measurement plane to parallel planes along the optical axis. Initial results of laboratory characterization of complex radiation pattern measurements of a 350 GHz, 880 pixel microwave kinetic inductance focal plane array are presented here. The multiplexing readout allow the whole array to be measured with just two beam pattern scans. This allows rapid characterization of a large field camera, comparable to that required by current, planned, and future instruments.

Introduction

In just the last two decades, astronomical microwave kinetic inductance detectors (MKID) instruments have grown from single pixel prototypes to large focal plane arrays (FPAs) of several hundreds of pixels. Until recently, the only option available to measure the radiation pattern of these detectors was with amplitude-only measurements, as direct detectors do not intrinsically record phase information from coherent sources. With the introduction of a phase reference system demonstrated in [1], it is possible to record the full complex field structure of direct detector arrays. We have expanded on the previous work for a single array pixel to a large MKID array consisting of 880 pixels.

A complex field analysis is more data intensive than the analysis of simpler power patterns, but opens the door to a much more complete set of analysis techniques. In addition to constraining beam fitting routines in more degrees of freedom, complex field analysis allows spatial filtering of stray light from off-axis sources, full beam reconstruction by propagation to arbitrary planes along the optical axis, determination of pointing offsets from a single measurement scan plane, and full wave front error analysis [2]. The beam fitting routine we adopt corrects for misalignment between the scanning plane and optical system of the measurement set-up, reducing the complexity of the measurement system verification process.

We point out that though MKIDs were analyzed in this research, the measurement technique we use here is applicable to other direct detector devices, in the full range of the frequency spectrum. In particular, the methods we employ for rapid analysis of large datasets can be adopted for large FPA analysis.

Methods

The MKID FPA analyzed here consists of high-Q, $\lambda/4$ resonators [3] on a silicon substrate, each with a resonant frequency in the range 4-8 GHz. Optical coupling is achieved with a twin-slot antennae [4], combined with elliptical lens [5]. The twin-slot is integrated into the MKID, where the ground plane is sputtered NbTiN 500 nm thick and the central line is sputtered Al 55 nm thick. The Al section acts as the active area of the device, as its kinetic inductance—and hence the MKID resonant frequency—are modified by the optical loading. The antenna is optimized for 350 GHz, while an on-chip stray light mesh absorber of 40 nm Ta is integrated on the back of the detector chip [6]. A laser-machined silicon lens array is aligned on the array using alignment markers on the back of the detector chip. The array has 880 pixels with hexagonal packing and a pixel pitch of 2 mm. All MKIDs are coupled to single throughline, allowing all 880 pixels to be read out with a single co-axial readout line. The readout system [7] has only 2 GHz of instantaneous bandwidth, so two separate scans of the array are required to cover the full 4-8 GHz readout spectrum. In the presented measurements, the array is mounted in a large field-of-view optical system [6], allowing measurements to be made with sources in the reimaged focal plane.

We measure the complex beam pattern of the incoherent detector array by implementing an optical scheme involving 2 sources in a heterodyne configuration. The amplitude and phase signal of each pixel is determined by the relative signal strength of the two monochromatic sources, which are offset by a small frequency difference such that they modulate the MKID at the difference frequency. As the source is scanned across the image

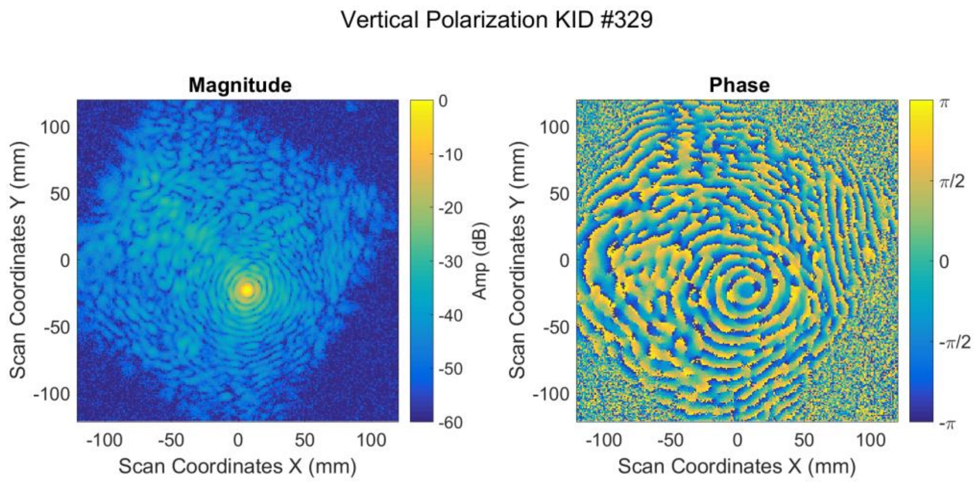

Fig. 1. Magnitude (right) and phase (left) of a central pixel of the array. The rotation of the image plane with respect to the scan plane is obvious. The phase structure shows surprising coverage across the image plane given the mechanical and thermal instabilities of the system.

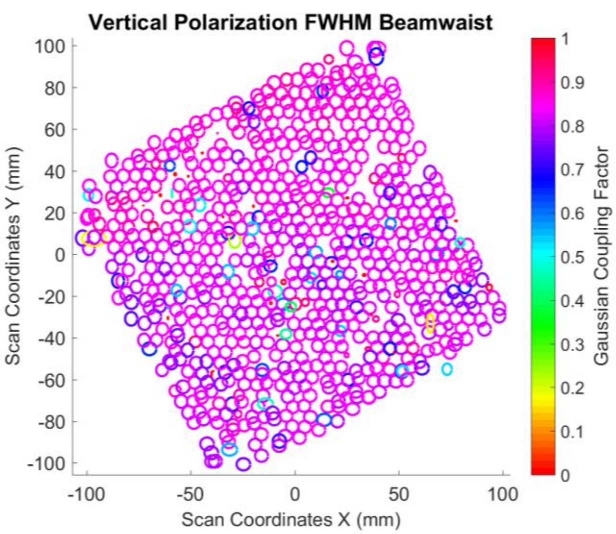

Fig 2. Fitted beamwaists across the array of the measurement with the source probe aligned horizontally to the scan plane. The color of each beam corresponds to the normalized gaussianity of each beam.

plane, the amplitude and phase of the detector response changes proportionally to the path difference between the sources. The detection scheme is similar to that presented in [1].

Optical coupling of the LO to the entire array can be achieved with a thin beam splitter located at the optical pupil in the warm reimaging system. At the pupil, all pixel beams overlap spatially but can be distinguished by their beam pointing angle. To improve coupling for all pixels at larger angles, the LO is deliberately defocused. In this optical system the pupil is directly available with little perturbation to the optics.

RESULTS

Timeseries signals from each pixel in the FPA were converted to a complex field map. The amplitude and phase of the entire scan range for a representative pixel is shown in Figure 1. There is a strong peak signal in the amplitude maps but a large dispersed signal at the ~-40 dB level present throughout the entire map. We have attributed this signal to diffraction and imperfect optics; in detector substrate and lens array stray light is suppressed by the on-chip absorber as discussed in [6]. The phase map shows a spherical phase center, near the amplitude center, and the ring-like structure is caused by the phase ‘wrapping’ from -π to π. For the subsequent analysis, we use only a portion of the field map corresponding to an area of 8x the expected beamwidth in the near field of the system. This area was chosen to include at least 2 phase wraps in the selected area to determine whether these points were actual wraps caused by the spherical phase roll-off or from nulls in the amplitude map where phase jumps due to the sign change in the complex field map.

We then take the selected area from each pixel in the complex field maps and use a Gaussian-Hermite fitting algorithm to determine the Gaussian beam efficiency and waist parameters for each pixel in both polarizations, as described in [1]. This routine fits for the center position of the beam as well as the beam width independently in X and Y. Fig. 2 shows the fitted beam locations and full width, half maximum (FWHM) elliptical beamshapes for across the entire FPA in a single polarization of the source probe.

CONCLUSION

Analysis of this large dataset is still ongoing, but initial results confirm that complex field parameters can be measured easily for a large focal plane MKID array. The range of analysis shown here exceeds that would be available for more standard, power pattern measurements. These results show that to first order, the beams appear consistent across the array and agree with the designed parameters.

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References

[1] K.K. Davis, W. Jellema, S.J.C. Yates, L. Ferrari, J.J.A Baselmans, K. Khono, D. Thoen, V. Muregesan, A. Baryshev, “Proof of Concept Demonstration of Vector Beam Pattern Measurements of Kinetic Inductance Detectors”. IEEE Thz Sci. and Tech. Jan. 2017. doi: 10.1109/TTHZ.2016.2617869

[2] W. Jellema, “Optical Design and Performance Verification of Herschel-HIFI,” PhD. Thesis, 2015, University of Groningen, the Netherlands

[3] P. K. Day, H. G. LeDuc, B. A. Mazin, A. Vayonkias, J. Zmuidzinas, “A Braodbans Superconducting Detector Suitable for Use in Large Arrays,” *Nature.* vol. 425. pp 817-821. October, 2013. doi:10.1038/nature02037

[4] J. Zmuidzinas and H. G. LeDuc, “Quasi-optical slot antenna SIS mixers,” *IEEE Trans. on Microw. Theory Techn.,* vol. 40, no. 9, pp. 1797–1804, Sep 1992. [Online]. Available: http://dx.doi.org/10.1109/22.156607

[5] D. F. Filipovic, S. S. Gearhart, and G. M. Rebeiz, “Double-slot antennas on extended hemispherical and elliptical silicon dielectric lenses,” *IEEE Trans. on Microw. Theory Techn*., vol. 41, no. 10, pp. 1738–1749, Oct 1993. [Online]. Available: http://dx.doi.org/10.1109/22.247919

[6] S. J. C. Yates, A. M. Baryshev, O. Yurduseven, J. Bueno, K. K. Davis, L. Ferrari, W. Jellema, N. Llombart, V. Murugesan, D. J. Thoen, J. J. A. Baselmans. "Surface wave control for large arrays of microwave kinetic inductance detectors", accepted for publication in *IEEE Trans. THz Sci. Tech.*

[7] J. van Rantwijk, M. Grim, D. van Loon, S. Yates, A. Baryshev,and J. Baselmans, “Multiplexed readout for 1000-pixel arrays of microwave kinetic inductance detectors,” *IEEE Trans. Microw. Theory Techn.,* vol. 64, no. 6, pp. 1876–1883, June 2016. [Online]. Available: http://dx.doi.org/10.1109/TMTT.2016.2544303