National Aeronautics and Space Administration

FY23 Topic Areas Research and Technology Development (TRTD)

Hierarchical Antennas for mm-wave Spectroscopy on a Chip

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Strategic Focus Area: Direct/Coherent Detectors and Arrays

Objectives & Background:

Direct detection, superconducting, spectrometers-on-a-chip → cover very large spectral bandwidths, map the universe over large redshift range in 0.1-2 THz regime and diffraction-limited.
Current spectrometers have single-size optical receiving element
- limited in redshift range (ν_{max}: ν_{min} = 1.65:1),
-optical efficiency varies >2 because diffraction spot size mismatched.
→The potential for 3D mapping with multiple spectral lines becomes limited.

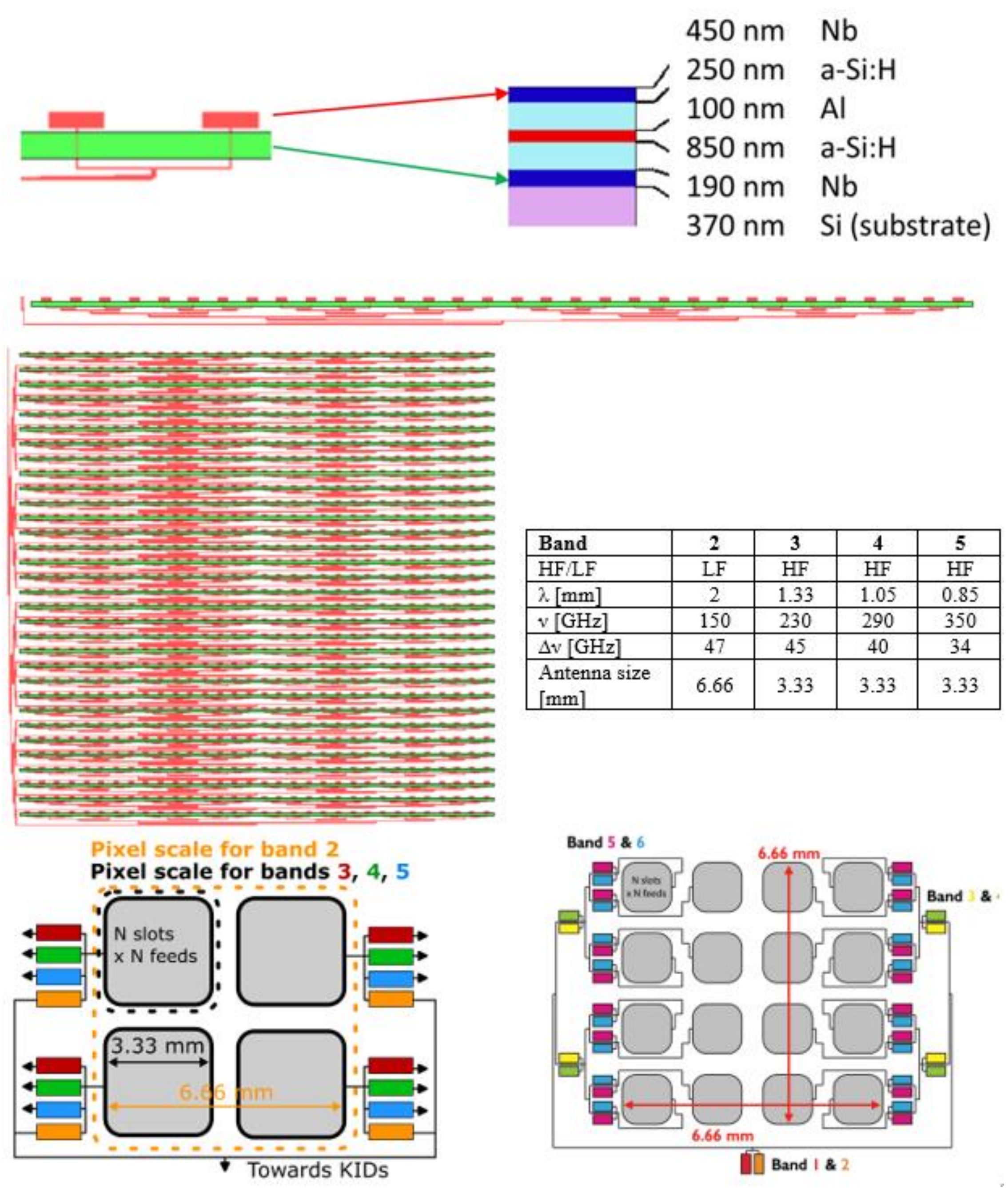
Hierarchical phased-array antennas can solve this problem. The fundamental optical receiving element is a phased array of slot dipoles in a superconducting ground plane illuminated through a silicon substrate and coherently summed (like phased-array radar). Frequency-selective summing of such antennas enables the spectrometer pixel size to scale with wavelength to match the diffraction spot size over a fractional bandwidth much larger than 1.65:1. **Our objective was to demonstrate this summing.**

Significance to JPL/NASA:

Enables spectrometer-on-a-chip technology under development by JPL and NASA more generally (SuperSpec at JPL/Caltech, μSpec at GSFC) to cover potentially much broader bandwidths than possible without this innovation --- expanding from 1.65:1 to 5.5:1 or perhaps even greater. With wide-bandwidth AR structures for silicon under development (Golwala silicon AR structure APRA) and microstriplines capable of reaching to 2 THz (Golwala a-Si:H and Cunnane MgB2 APRAs)→ FoV-filling spectroscopic focal planes for ground-based telescopes and NASA missions that can map the universe in 3D using CO, HCN, [CII], [NII], [OI], and [OIII].

Approach:

Fundamental antenna element



Band	2	3	4	5
HF/LF	LF	HF	HF	HF
λ [mm]	2	1.33	1.05	0.85
ν [GHz]	150	230	290	350
Δν [GHz]	47	45	40	34
Antenna size [mm]	6.66	3.33	3.33	3.33

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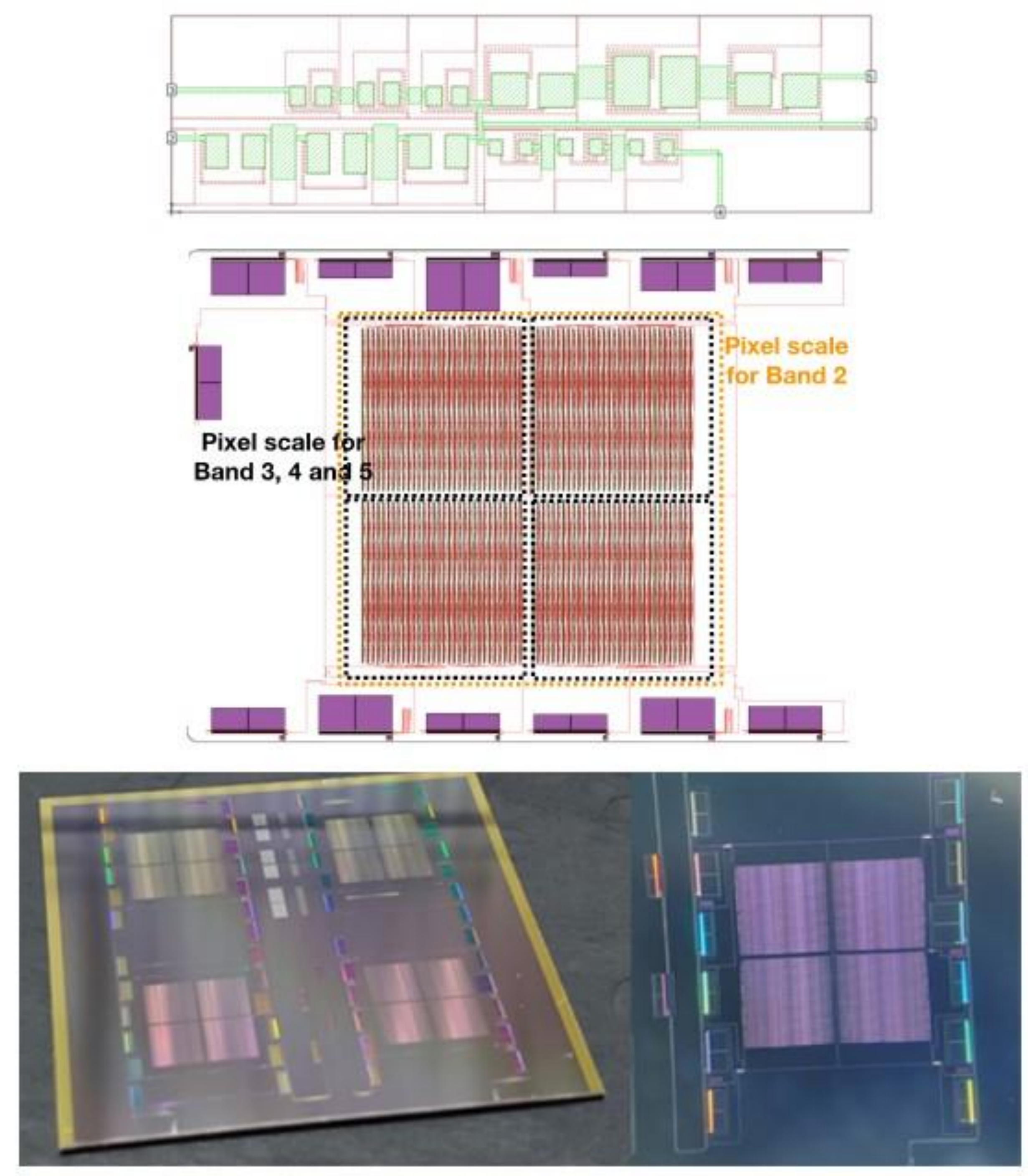
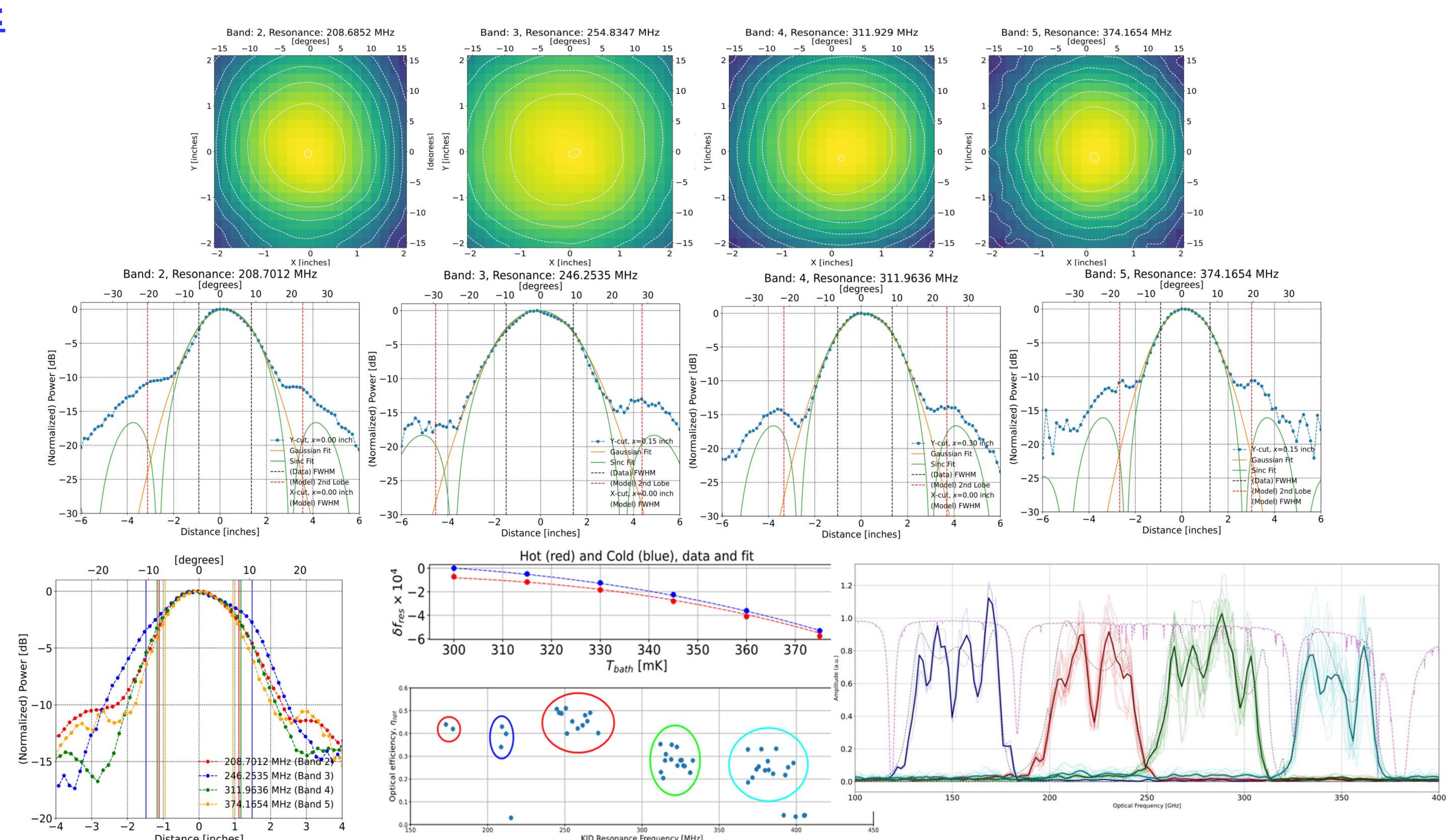
Bandpass filters/ 2-scale hierarchy design



(Top) Bandpass filter design. Green squares: capacitor pads, red spirals: inductors, green line entering from the right is the microstripline from the antenna. The four bands connect to the junction at the center. The bands are, clockwise from upper left: B4, B2, B5, and B3. *(Middle)* Mask for two-scale antenna. Each sub-element is fundamental antenna element. BPFs are at the outer four corners of the summed antenna, and the four B2 lines from each sub-element join first at the left and right sides and then at the center and exit at the top. The KID capacitors are visible around the edges of the antenna. There are two each B3, B4, B5 KIDs at the bottom and the top, and the one remaining detector that is different is the B2 KID. *(Bottom left)* Photo of fabricated chip with four copies of the hierarchical antenna. *(Bottom right)* Zoom-in picture on a single hierarchical antenna and its KIDs.

Results:

(First and second row, third row left) Beam maps in 2D and 1D. The third row plot compares the FWHM of the different bands and shows the B2 beam of the hierarchically summed antenna has approximately the same width as the fundamental antenna B4 beam, which makes sense give the factor of 2 in frequency and the factor of 2 in antenna size. *(Third row, right)* Hot/cold blackbody load example measurement and optical efficiency as a function of KID readout frequency. The four mm-wave spectral bands are represented by the four colored ovals (B2-B5 left to right). Two of the B3 resonators have shifted away from their design readout frequencies but are otherwise functional. One B2 resonator appears to have become disconnected from its microstripline given that it displays very low optical efficiency. Three resonators near 400 MHz are designed to be "dark" — i.e., not connected to antennas — as a test for direct absorption in the KIDs rather than via the microstripline. *(Bottom row)* Measure bandpasses (thin: individual KIDs; thick: average over each band) compared to design bandpasses (thin dashed) and atmospheric transmission (magenta dashed). B5 will be corrected in the future to fit within the atmospheric transmission window.



Publications:

S. Shu, A. Beyer, F. Defrance, J. Sayers, and S. Golwala, "Design of a multi-chroic kinetic inductance detectors array using hierarchical phased array antenna," *Journal of Low Temperature Physics* 209:330 (2022), https://doi.org/10.1007/s10909-022-02890-x.
F. Defrance et al., "Hierarchical phased-array antennas coupled to lumped-element aluminum KIDs: a scalable architecture for multi-band millimeter/submillimeter focal planes," talk presentation (LTD-20), Daejon, Korea, 2023.
J.-M. Martin, J. Kim, et al., "Antenna Design and Beam Performance of Millimeter/Submillimeter Hierarchical Phased-Array Antennas Coupled to Lumped-Element Aluminum KIDs," poster presentation at (LTD-20), Daejon, Korea, 2023.
J. Kim, J.-M. Martin et al., "Hierarchical Phased-Array Antennas Coupled to Lumped-Element Aluminum KIDs: Band-Defining Millimeter/Submillimeter Filter Design and Characterization," poster presentation (LTD-20), Daejon, Korea, 2023.
J.-M. Martin et al., "Hierarchical phased-array antennas coupled to lumped-element aluminum KIDs: a scalable architecture for multi-band millimeter/submillimeter focal planes," submitted to *Journal of Low Temperature Physics*, *Proceedings of the Twentieth International Conference on Low-Temperature Detectors (LTD-20)*, Daejon, Korea, 2023.

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