Development of Space-Optimized Bolometer Arrays for LiteBIRD

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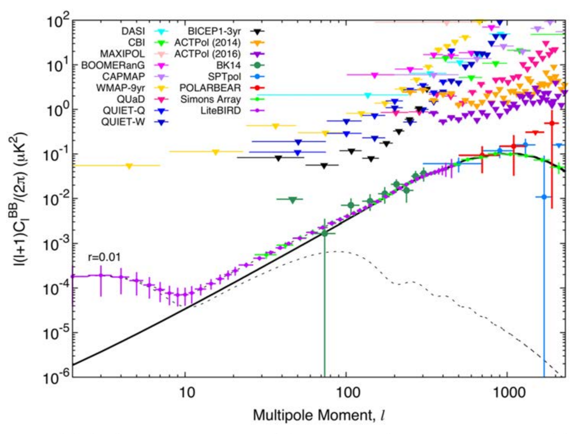
Abstract

Science Motivation

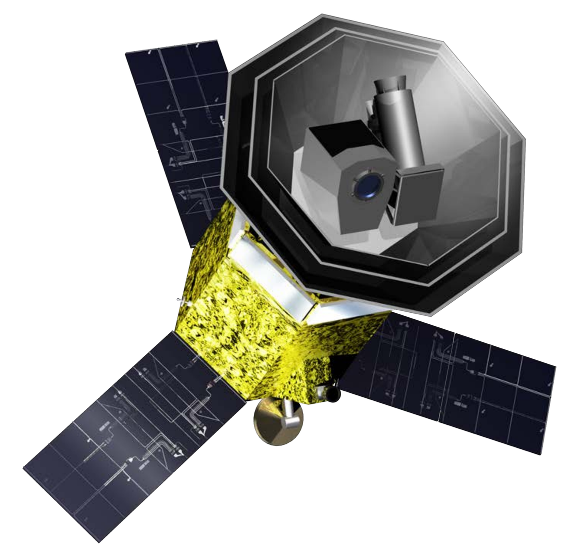
A primary science goal of cosmic microwave background (CMB) cosmology is measuring the degree-scale B-mode polarization sourced by inflationary gravitational waves. A significant detection would confirm inflation and aid in differentiating various models. The energy scale of inflation and the amplitude of the degree-scale B-mode polarization are proportional to the tensor-to-scalar ratio **r**. An experiment searching for this signal requires a large number of sensitive detectors covering a broad range of frequencies with superb control of systematics.



Published measurements of CMB B-mode power spectra with projections for LiteBIRD and Simons Array. Circles with vertical bars show central values and errors, while triangles are upper limits (Hazumi et. al. 2019)

LiteBIRD Overview

JAXA has selected LiteBIRD for a strategic L-class mission to search for the imprint of gravitational waves from inflation in the polarization of the CMB. The goal is to measure the tensor-to-scalar ratio with a total uncertainty of δr<0.001. It will be launched aboard JAXA's H3 rocket in 2028 into an L2 orbit where it will observe for three years. It will survey the full sky at degree-angular scales in 15 frequency bands from 34 to 448 GHz. The wide frequency range covered will enable galactic foregrounds to be removed from the primordial signal. To cover such a wide bandwidth, three telescopes will be used: a reflective low-frequency telescope (LFT) and refractive mid- and high-frequency telescopes (MFT and HFT).

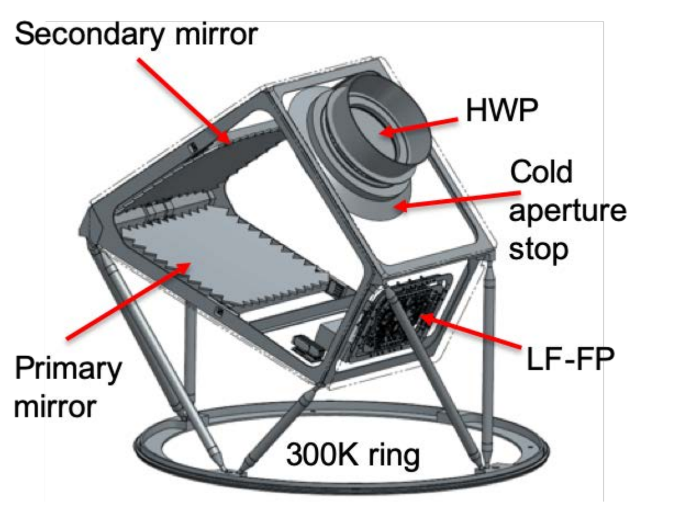


Rendering of the LiteBIRD spacecraft with its three telescopes. (JAXA)

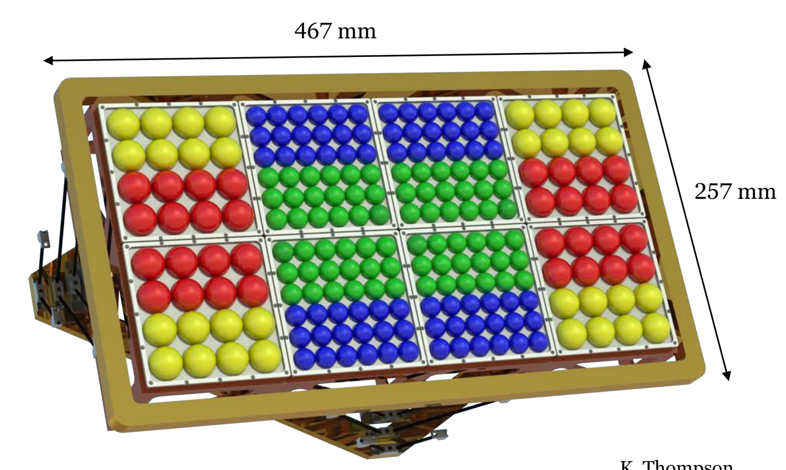
International Consortium

LiteBIRD is an international project with partners from around the world. JAXA will provide the launch vehicle, payload module, 4K cooler, and LFT. The European consortium will provide the sub-K cooler, MFT and HFT. Canada will supply the warm readout system. The US hardware contributions will be the focal planes with integrated SQUID readout for all three telescopes and the 1.8 K adiabatic demagnetization refrigerator. More than 4500 TES bolometers cooled to 100 mK will provide a sensitivity 40 times greater than current experiments.

LiteBIRD Low Frequency Telescope



Sekimoto et.al 2018 SPIE

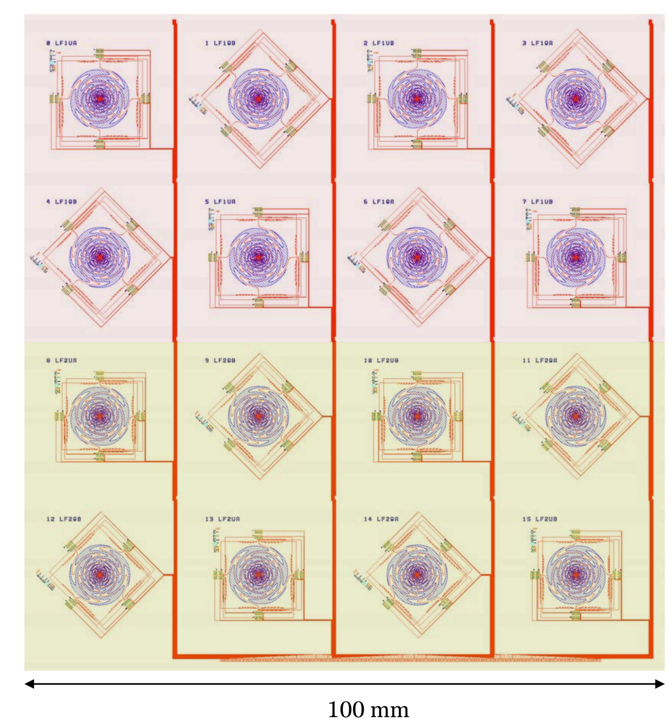


K. Thompson

The low frequency telescope is a Crossed-Dragone design, modulated by a half-wave plate, and covers 9 bands. The primary mirror is 80 cm and provides an angular resolution of 0.5° at 100 GHz.

The low frequency focal plane (LF-FP) has 4 pixel architectures LF-1, LF-2 , MF-1, MF-2, each covering three bands with some overlap. A total of 1248 antenna-coupled TES bolometers will populate the focal plane. Hemispherical lenslets will form the beam of each pixel.

Low Frequency Detector Array Design



Array architecture of the LF-1/2 detector wafer.

The 6 lowest frequency bands are covered by two trichroic pixel designs. The pixels have alternating Q/U polarization orientations and alternating antenna handedness.

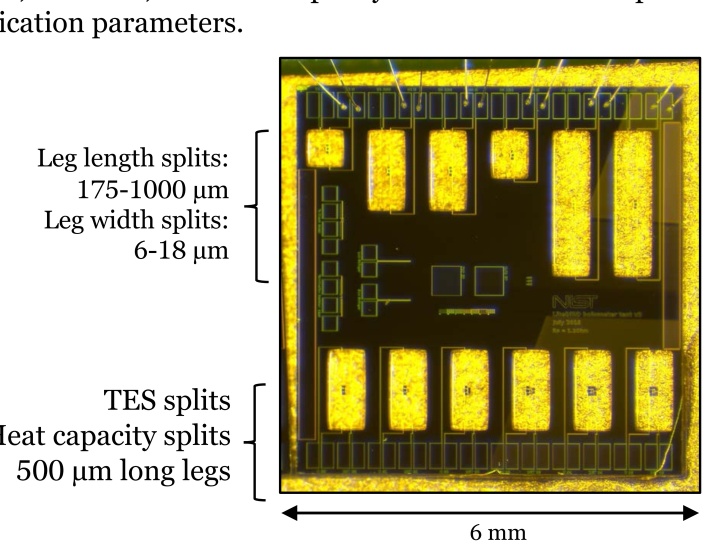
Pixel Type	Band Center [GHz]	Bandwidth [%]	Saturation Power [pW]
LF-1	40	30	0. 90
	60	23	0. 73
	78	23	0. 70
LF-2	50	30	0. 95
	68	23	0. 70
	89	23	0. 70

The saturation powers are an order of magnitude lower than typical ground-based experiments. This is an active area of research and development.

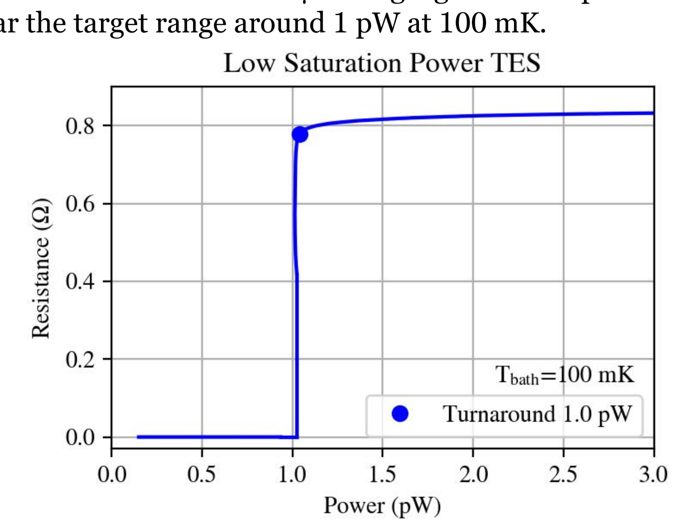
Bolometer Measurements and Design Optimization

Bolometer Test Chip

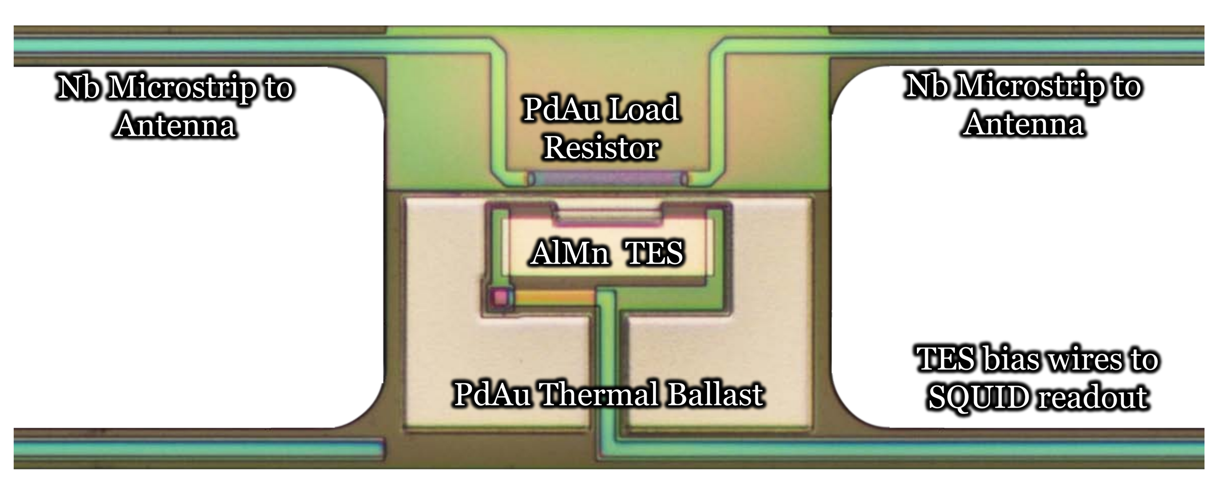
Bolometers with a wide array of properties have been fabricated at NIST and tested at CU Boulder. This chip has 12 bolometers with variations on bolometer leg length, leg width, TES size, and heat capacity to determine the optimal fabrication parameters.

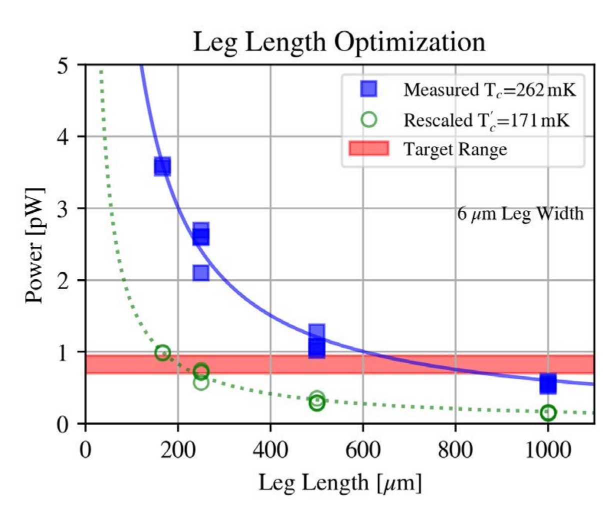


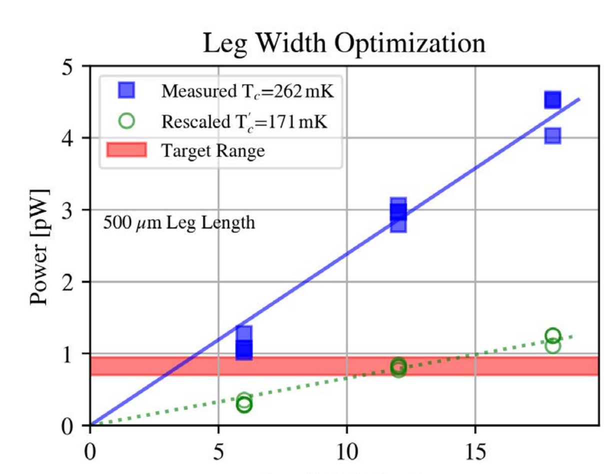
The bolometers with 1000 μm long legs had bias powers near the target range around 1 pW at 100 mK.



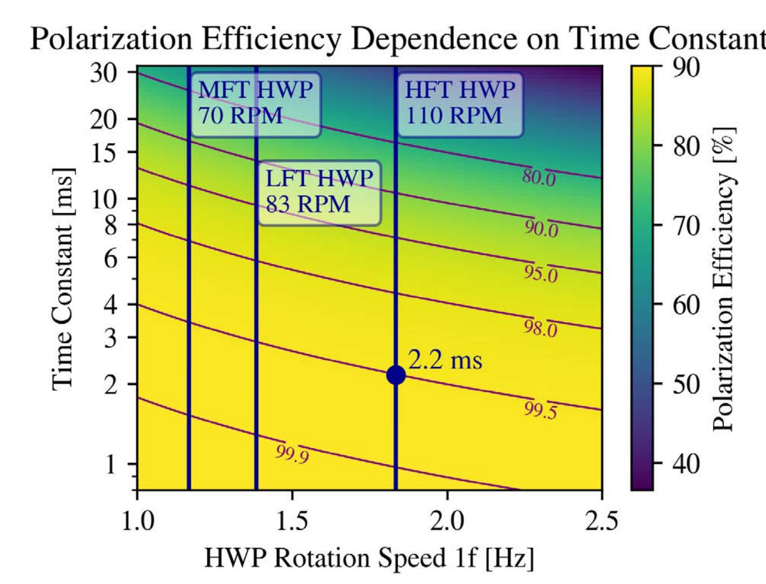
Bolometer Island

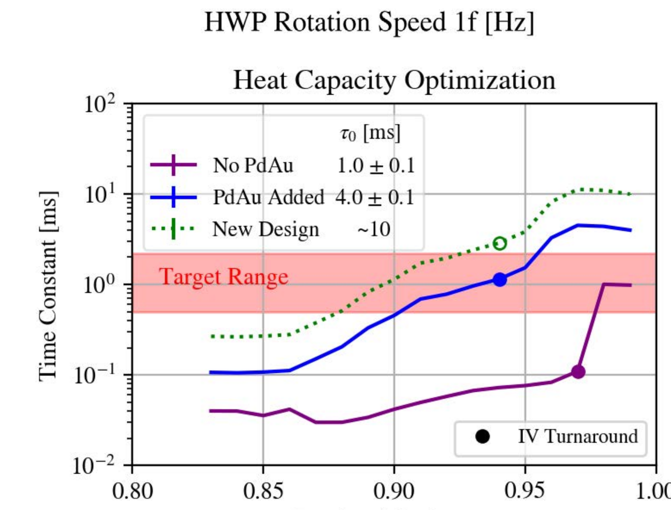






The saturation power can be tuned by the bolometer geometry. Adjusting the length and width of the legs controls the flow of power across the thermal link to the bath. The T_c of these devices was higher than targeted, but we can scale the powers to the correct Tc once the thermal conductance parameters are measured. For the next iteration of TESs, we chose leg widths of 10 to 15 μm to span the target saturation power range for their mechanical robustness compared to the 6 μm width.





The bolometer time constant can be tuned with the addition of PdAu metal on the island. The time constant must be fast enough to not reduce the half-wave plate 4f modulation and slow enough to not exceed readout bandwidth. The time constants should be faster than 2.2 ms to keep polarization efficiency above 99.5%. The bolometer is too fast when there is no PdAu. Adding PdAu slows the bolometer into the target region and the new design slows it down further.

Low Frequency Prototype Pixel

Baseline Design

The baseline prototype pixel design contains:

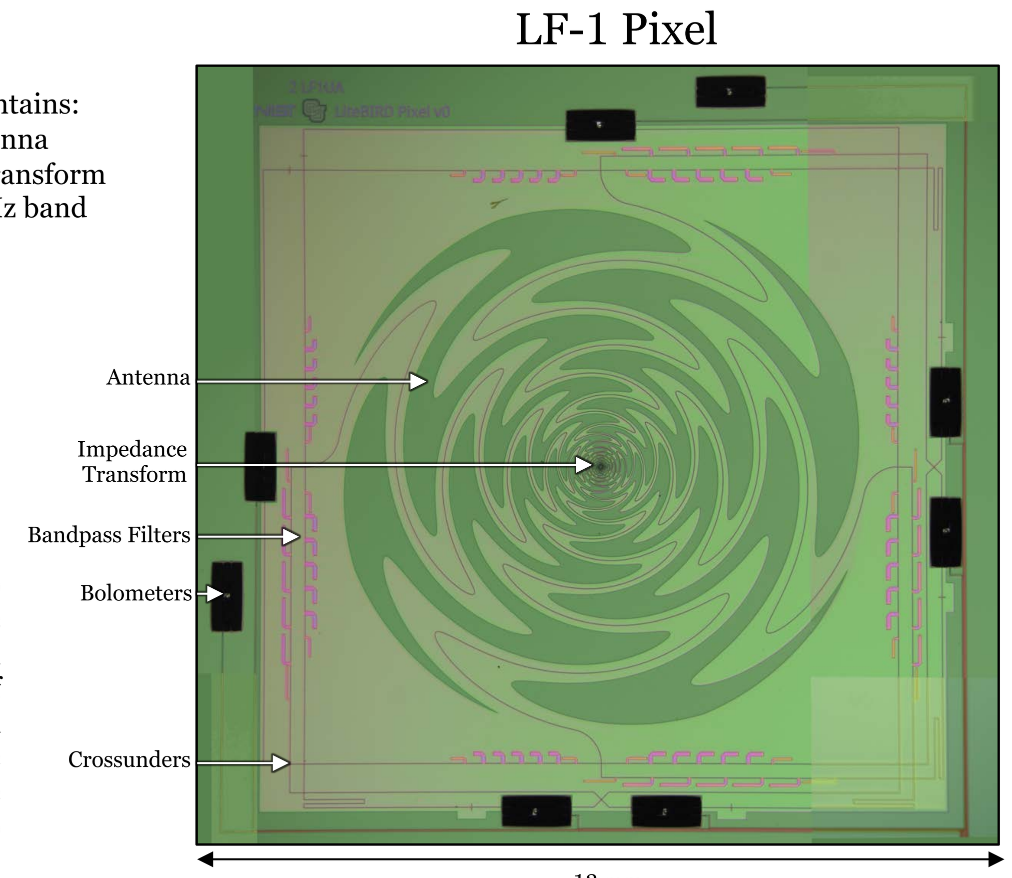
- 9 mm diameter 20-cell sinuous antenna
- Feedline with 53:10 Ω impedance transform
- 7-pole triplexer filters 40/60/78 GHz band
- 6 optically-coupled bolometers
- 2 dark bolometers

Pixel Splits

1. Single band 60 GHz 7-pole filter
2. Single band 60 GHz 5-pole filter
3. Differential microstrip routing through antenna arms

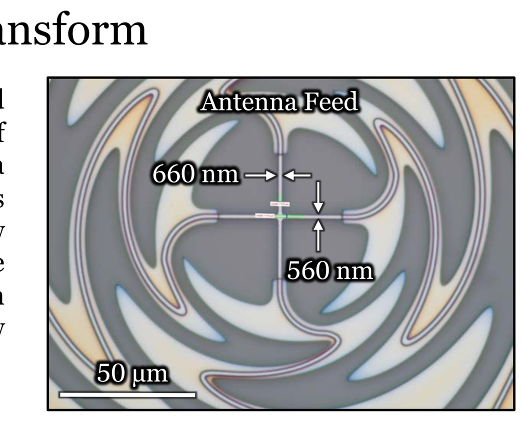
The first pixel split allows us to compare the efficiency of a single band filter to the triplexer. We can compare the in-band transmission of 5- and 7-pole filters with the second split. The third split will test the dielectric loss by comparing the optical efficiency of the two polarizations.

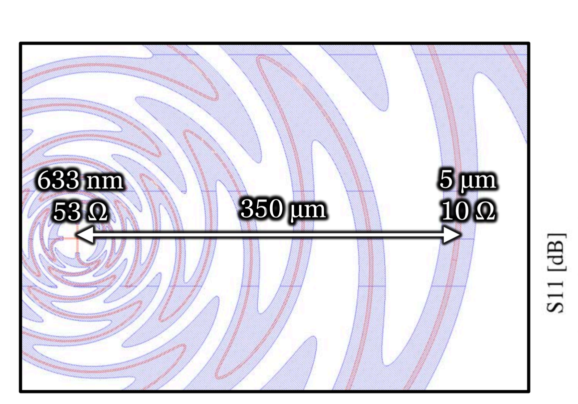
LF-1 Pixel



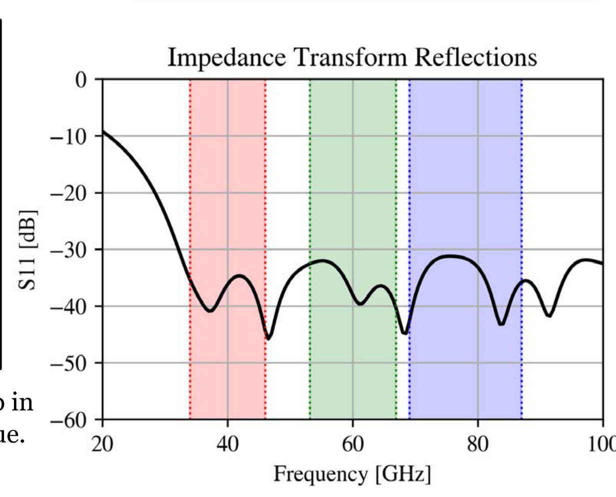
Impedance Transform

The 53 Ω impedance of the differentially fed antenna must be matched to the 10 Ω impedance of 5 μm the microstrip line; this is accomplished with a Klopfenstein taper. The NIST SiN dielectric layer is 350 nm thick which requires an extremely narrow line width of 633±100 nm. This taper allows the structure to be compact thus minimizing the length of the narrow microstrip. NIST achieved this narrow line width on the first attempt.



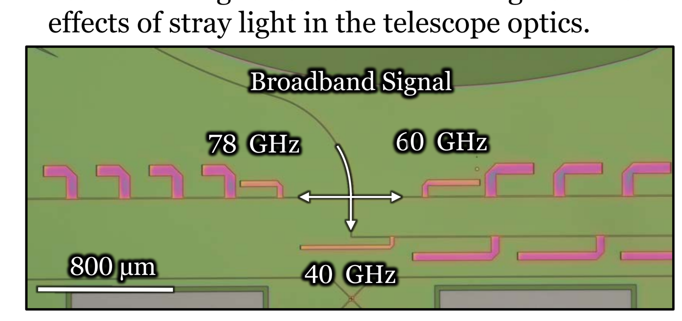


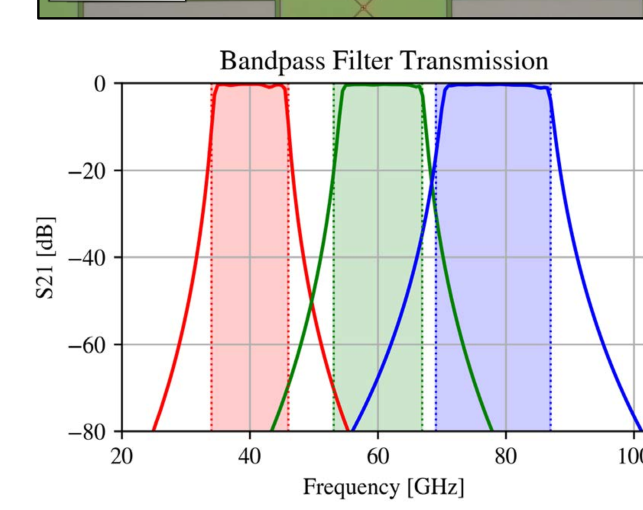
Detailed view of the pixel center with microstrip in red, antenna slot in white, and Nb ground in blue.



Bandpass Filters

The bandpass filter is 7-pole quarter-wavelength short-circuited stub design. The use of a higher-order filter mitigates the effects of stray light in the telescope optics.





Conclusions

- We have determined the optimal fabrication parameters for space-based TES bolometers based on measurements.
- Using these parameters, we designed another iteration of the bolometer test chip.
- We have designed a prototype pixel with a sinuous antenna, bandpass filters, and impedance transforms and coupled it to the optimized bolometer.
- We have recently made LF-1 prototype pixels and bolometer test chips at NIST.

References

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