# Feedhorn-Coupled TES Polarimeters for Next-Generation CMB Instruments

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**Abstract.** The next generation of cosmic microwave background (CMB) polarization experiments targeting the signatures of inflation will require unprecedented sensitivities in addition to careful control of systematics. With existing detector technologies approaching the photon noise limit, improvements in system sensitivities must come from ever-larger focal plane arrays of millimeter-wave detectors. We report on the design and performance of microfabricated planar orthomode transducer (OMT) coupled TES polarimeters and silicon micromachined platelet feedhorns optimized for scaling to large monolithic arrays. Future versions of these detectors are targeted for deployment in a number of upcoming CMB experiments, including ABS, SPTpol, and ACTpol.

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## INTRODUCTION

Detailed studies of the polarization of the cosmic microwave background (CMB) promise rich new insights into the universe. Measurements of the E-mode polarization will augment CMB temperature power spectrum measurements by helping to constrain cosmological parameters and breaking model degeneracies. B-mode polarization at degree angular scales is expected to be a unique signature of primordial gravitational waves from the epoch of inflation, and as such a window onto physical processes at energy scales unattainable with particle accelerators. At smaller angular scales, gravitational lensing of E-modes into B-modes would provide valuable information about the distribution of matter between recombination and the present universe.

A number of experiments in development are now targeting the CMB polarization at various angular scales to pursue the above-mentioned science goals. One of the many challenges these new generation of experiments will attempt to overcome is one of sheer sensitivity: because existing millimeter-wave detector technologies already operate close to the background photon noise limit, further gains in total instrument sensitivity must come from the ability to field ever-larger arrays of densely packed pixels.

Recently, BICEP[1] and QUAD[2] have made the first high signal-to-noise measurements of the first four acoustic peaks in the E-mode spectrum, and have set unprecedented upper limits on the magnitude of the B-modes. While significantly improving on previous efforts, BICEP's initial upper limits are an order of magnitude above the expected levels for a tensor-to-scalar ratio of $r = 0.1$, and QUAD's upper limits at smaller angular scales are nearly two orders of magnitude above the expected levels of gravitationally-lensed B-modes. Large gains in sensitivities are needed if the next-generation experiments are to achieve their science goals.

One of the challenges of building a large-format array of CMB polarimeters lies with the choice of radiation-coupling mechanism onto the bolometers. Experiments such as BICEP and QUAD used individually electroformed Cu corrugated feedhorns. While they provide good control of sidelobes, wide-band performance and

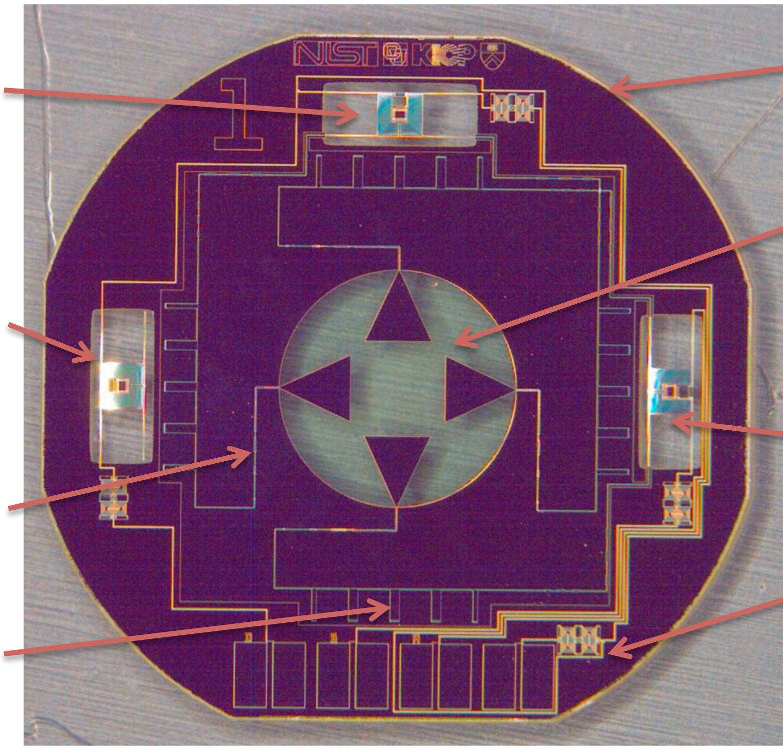


**FIGURE 1.** Prototype 145 GHz Polarimeter.

low cross-polarization, this method quickly becomes impractical for implementing arrays of several hundreds to thousands of pixels. BICEP and QUAD also used polarization-sensitive micromesh bolometers that were hand-assembled into individual modules, which would also be impractical for large-format arrays.

To address these issues, we propose a monolithic, all-silicon focal plane architecture using micromachined Si platelet feedhorns and microfabricated planar orthomode transducers (OMTs) that couple the incoming radiation to an array of multiplexed superconducting transition edge sensors (TESs). This paper is intended as a brief and descriptive overview of the design and measurements of single-pixel prototype OMT-coupled polarimeters and stacked Si platelet waveguides. Companion papers elsewhere in this volume provide in-depth technical detail, and are referenced in relevant sections below.

## DESIGN OVERVIEW

A feedhorn array consisting of stacked, metalized Si wafers—with each wafer defining a single corrugation along the profile of a feedhorn—retains all of the advantages of traditional corrugated feedhorns while eliminating many of the disadvantages. Such a monolithic array of feeds can be densely packed, and is significantly lower in thermal mass than a comparable metal platelet array. It is also perfectly matched with a monolithic detector array wafer in thermal contraction, eliminating problems with precision alignment.

The Si platelet feedhorns are integrated directly with a monolithic detector array consisting of OMTs and other superconducting planar transmission line components that take full advantage of existing photolithographic techniques.

Figure 1 shows a 5-mm diameter single-pixel prototype polarimeter fabricated at NIST and designed to couple to a 1.6-mm diameter circular waveguide for operation at 145 GHz. Preliminary testing was carried out by mounting the single pixels onto specially designed metal modules that provide $\lambda/4$ backshorts and appropriate interfacing to existing metal feedhorns.

## OMT & CPW-to-microstrip transition

The planar OMT is optimized for maximum coupling to the fundamental TE11 mode of the corresponding 1.6 mm diameter circular waveguide. The OMT consists of four triangular Nb probes—with orthogonal pairs coupling to X and Y polarizations—that taper to 5 $\mu$m wide Nb lines at the waveguide wall and transition into a coplanar waveguide (CPW). Simulations of the fabricated design have shown greater than 96% coupling of the TE11 mode, with $\sim 2\%$ reflected out and $\sim 1\%$ radiated into the 50 $\mu$m airgaps above and below the relieved OMT membrane.

While the rest of the superconducting components on the polarimeter make use of Nb microstrip lines, coupling from the circular waveguide to CPW is easier because of the higher characteristic impedance CPW compared to microstrip. A numerically optimized transition from CPW to microstrip is then made for matching to the rest of the superconducting circuitry.

Details of the OMT design and its optimization, as well as the CPW-to-microstrip transition, are available in McMahon et al.[3]

## Microstrip filters

The existing prototype polarimeters are designed for operation at a nominal band-center of 145 GHz and a fractional bandwidth of 25%. The spectral band is defined by 5-pole $\lambda/4$ shorted stub filters (see Figure 2). These resonant filters transmit at odd harmonics, and the leakages above the main band must be attenuated. This is accomplished by using two back-to-back stepped-impedance low-pass filters with staggered cut-off characteristics. The out-of-band transmission has been simulated to be $\sim -30$ dB or lower.

## Lossy absorber and TES

After filtering, the microstrip lines terminate onto free-standing bolometer islands (see Figure 3). The lossless

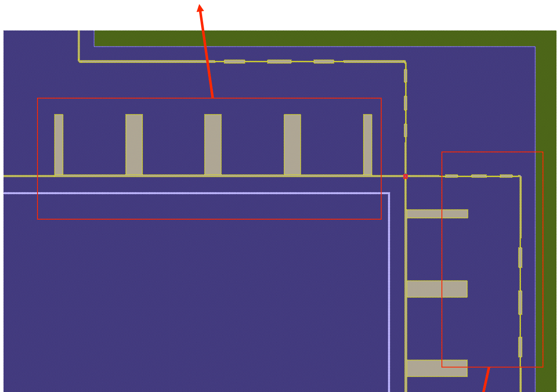


**FIGURE 2.** Microstrip filters.

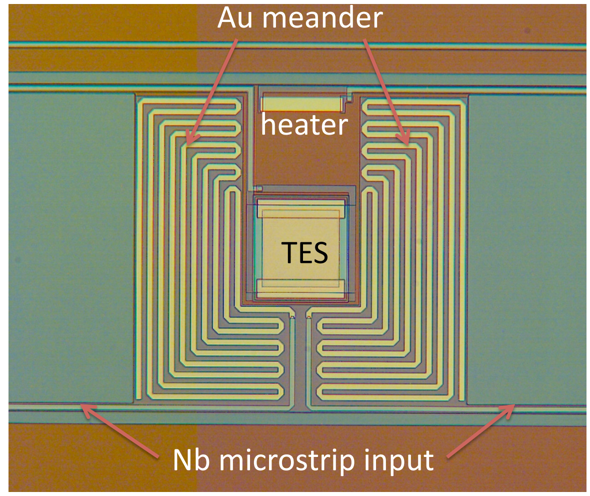


**FIGURE 3.** Relieved TES island.

Nb lines abruptly transition into long meanders of lossy Au microstrip so that almost all of the incident power is absorbed. Simulations have shown the reflection to be $< -20$ dB across the entire spectral band. Because Au microstrip is well-matched to Nb, the reflection at the abrupt transition is minimal.

The absorbed power is then detected by a MoCu bilayer TES with nominal $T_c = 530$ mK and $R_n = 5$ m$\Omega$, appropriate for the time-domain SQUID multiplexed readout used in prototype testing thus far. A $\sim 2\ \Omega$ gold heater is available on the island for calibration and testing purposes. The thermal conductance to the 250 mK bath is determined by the silicon nitride legs that support the two Nb microstrip lines as well as the lines for TES and heater biases. By varying the aspect ratio of the nitride legs we have been able to target thermal conductance $G(T = T_c)$ of 50 to 600 pW/K, which cover the range of interest for both low-background CMB observations and ambient temperature load laboratory testing.

## Si platelet feedhorn

As a first step towards building monolithic arrays of Si platelet feedhorns, we have fabricated single stacks of various geometries to characterize the loss of metalized Si waveguides on a vector network analyzer (VNA). The VNA measurements show an upper limit of 0.15 dB/cm loss over $80-110$ GHz at room temperature. We expect this to become negligible at the operational temperatures below 1 K. Detailed report on the Si waveguide measurements is given in Britton et al.[4]

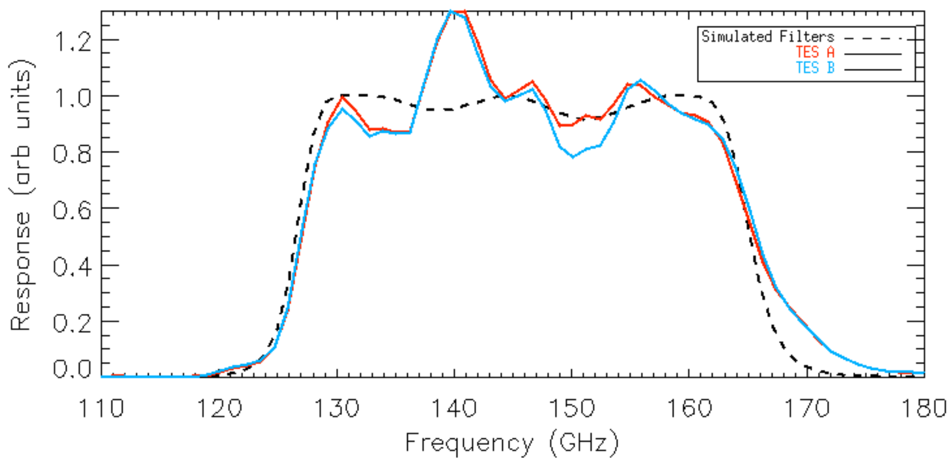


**FIGURE 4.** Measured vs. simulated spectral band.

## TEST RESULTS

A full set of dark characterization and a limited number of optical tests have been carried out on the prototype 145 GHz pixels. In summary, the OMT-coupled polarimeters have band-averaged optical efficiencies of $\sim 54\%$ and crosspolar coupling of $<\sim 4\%$. The optical efficiency may be improved by using CPW stub filters instead of microstrip if the loss is due to the dielectric. We have designed an OMT-coupled ring resonator to measure the dielectric loss and verify if it is dominating the end-to-end optical efficiency.

The spectral band definition of the stub filters is in excellent agreement with simulations (see Figure 4). There is significant out-of-band broadband coupling at higher frequencies, however, accounting for $\sim 50\%$ of the total integrated power. We have been able to eliminate this entirely by introducing lossy material into the 50 $\mu$m air-gap above the OMT membrane outside the diameter of the coupling circular waveguide.

Full detail of the optical tests is available in Bleem et al.[5] In addition, Austermann et al.[6] describes the results of the dark characterization of the prototype pixels, including measured uniformities of TES $T_c$, $G(T)$, time constants and noise properties. The modeling of the measured noise and complex impedance is presented in Appel et al.[7].

## FUTURE PLANS

Further optical and dark characterizations of the prototype pixels are currently being carried out. We are planning to measure the polarized beam response functions using metal corrugated feedhorns coupled to the single-pixel polarimeters to acertain that the OMT couples to the fundamental waveguide mode and that the beams are well-behaved. In addition, work is currently under way to extend the existing design to 90 and 220 GHz bands.

Future single-pixel polarimeters are planned for deployment in the ABS telescope in 2010, and monolithic 6" arrays of Si feedhorns/polarimeters are planned for the SPTpol and ACTpol telescopes starting in 2011.

## ACKNOWLEDGMENTS

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## REFERENCES

1. Chiang, H. C. et al., 2009, arXiv:0906.1181v2
2. Brown, M. L. et al., 2009, arXiv:0906.1003v2
3. McMahon, J. et al., 2009, this volume
4. Britton, J. et al., 2009, this volume
5. Bleem, L. E. et al., 2009, this volume
6. Austermann, J. E. et al., 2009, this volume
7. Appel, J. W. et al., 2009, this volume