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Optimizing Feedhorn-Coupled TES Polarimeters for Balloon and Space-Based CMB Observations

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Abstract Maximizing the sensitivity of balloon-based and space-based observations of the cosmic microwave background (CMB) requires detectors with substantially lower saturation power and background noise than ground-based observations, because of reduced atmospheric loading and lower photon noise. We have fabricated and tested prototype transition-edge sensor (TES) bolometers that have architecture identical to that used in feedhorn-coupled TES polarimeter arrays developed for ground-based CMB observations, but have saturation power appropriate for balloon-based or space-based observations (0.5 pW–7 pW). The operating resistance of these bolometers ($\sim$3 mΩ) is appropriate for readout with time-division or gigahertz frequency-division SQUID multiplexers. Dark bolometer measurements show that the noise levels are near the expected thermal-fluctuation-noise background ($<10^{-17}$ W/Hz$^{1/2}$), that the thermal response times are faster than the observation requirements, and that low-frequency $1/f$ noise can be strongly suppressed to <10 mHz by pair differencing. We report on the performance of the prototype devices and progress towards optimizing them for balloon-based and spaced-based observations.

Keywords Balloon · Cosmic microwave background · Feedhorn · Low-frequency noise · Polarization · Satellite · Transition-Edge Sensor

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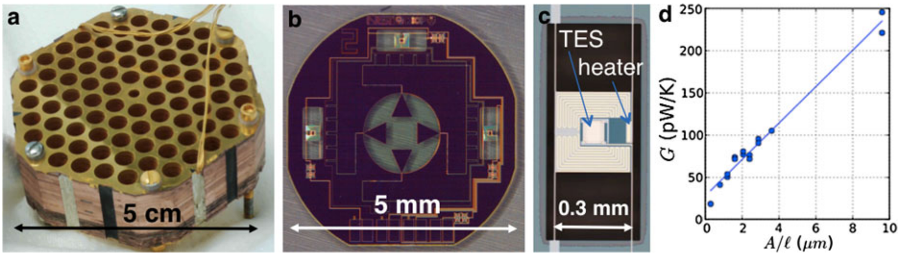

Fig. 1 (Color online) (**a**) An array of 84 gold-plated, silicon-platelet, corrugated feedhorns [11]. (**b**) A prototype Truce polarimeter [6]. (**c**) One of the ten low-T_c Truce compatible bolometer designs that were fabricated and tested. This is the type 1 design with the longest thermal isolation legs between the bath and the island, and therefore the lowest saturation power. The TES and heater are surrounded by Au microstrip. (**d**) Cross-sectional area, A, to length, l, ratio for the different bolometer leg designs versus measured G (*points*) and a fit to the data (*line*) to enable G optimization in new designs. The measurements in Fig. 2 are for types 1 and 4 devices, which have the smallest and fourth smallest A/l ratio

1 Introduction

Upcoming measurements of the cosmic microwave background (CMB) aim to probe the epoch of inflation, the sum of the neutrino masses, and dark energy [1, 2]. These measurements have the potential to detect the signature of inflationary gravity waves (IGW) in the CMB and thereby probe the energy scale of inflation ($\sim 10^{16}$ GeV), which is inaccessible by other means. A detection of IGW by upcoming ground-based or balloon-borne observatories would provide strong motivation for a next-generation CMB satellite, such as EPIC-IM [1, 3] or CoRE [4].

We are building corrugated feedhorn-coupled CMB polarimeter arrays with members of the Truce Collaboration [5, 6] that will be used in upcoming ground-based CMB polarization measurements by the Atacama B-mode Search [7] (ABS), the South Pole Telescope Polarimeter [8] (SPTpol), and the Atacama Cosmology Telescope Polarimeter [9] (ACTPol). An important difference between ground-based and balloon or satellite observations (and the primary motivation for the latter) is the reduced atmospheric loading and photon noise. Careful optimization of the detector design and performance is essential to take advantage of these improved observing conditions. We have fabricated and characterized the performance of prototype bolometers that are fully compatible with the Truce feedhorn-coupled polarimeter-array architecture and meet the performance requirements for balloon-borne (e.g. DeLITE) and space-based (e.g. EPIC-IM) CMB observations. We compare the measured bolometer performance to the instrument requirements, then describe next steps to continue the optimization.

2 Polarimeter Array Design

The Truce polarimeter array designs take advantage of the excellent polarization fidelity of corrugated feedhorns and the excellent noise performance of transition-edge sensor (TES) bolometers. The feedhorns are coupled to the bolometers via a superconducting Nb ortho-mode transducer that transmits the radiation through coplanar waveguide, then microstrip, to thermally isolated TES bolometer islands that measure the power in each polarization. The radiation is dissipated on the islands in Au microstrip, where it is sensed as a change in temperature by a TES operated in a state of negative electro-thermal feedback [10].

The polarimeter arrays for SPTpol and ACTPol include gold-plated silicon-platelet corrugated feedhorns [11] (Fig. 1). The advantages of using platelets include ease of manufacturing and higher packing density than that of individual feedhorns. The advantages of silicon include: higher-precision machining by use of a deep-reactive ion etching (DRIE) process; coefficient of thermal expansion identical to that of the detector arrays, which facilitates the required precision cryogenic alignment; a relatively high thermal conductivity; and a much smaller heat capacity than that of metals, making it relatively easy to cool the entire array and feedhorns to sub-Kelvin temperatures.

An additional advantage of the silicon-platelet feedhorns is the ability to DRIE ring-loaded corrugations that increase the single-moded feedhorn bandwidth [12]. Combining these features with superconducting hybrids in the polarimeter circuit provides roughly an octave of single-mode bandwidth. The increased bandwidth can be split into separate frequency bands, so that each feedhorn element is coupled to a multichroic polarimeter. This can provide a substantial increase in mapping speed for each element in the focal plane; for example, McMahon, et al. 2011 [12] projects that the planned multi-chroic array in ACTPol will achieve the full sensitivity of an optimized single-frequency 90 GHz array plus 70% of the sensitivity of an optimized 150 GHz array. This mapping speed increase is a major improvement for any instrument and especially for a balloon or satellite payload with a limited field of view. Alternatively, when detector readout (or power consumption) is a limiting factor, the additional bandwidth can simply be used to improve the single-frequency sensitivity.

Ultimately the sensitivity of a well designed and implemented wide-bandwidth detector will be limited by a combination of the astronomical photon noise, the instrument photon (and other systematic) noise, and the detector noise. The detector noise contribution can be minimized by lowering the T_c of the TES. Decreasing T_c also changes the thermal properties of the bolometer in that the thermal conductivity, G, and the heat capacity, C, both decrease for a fixed design. The decrease in G is easily compensated by increasing the ratio of cross-sectional area to length of the thermal connection to the bath (e.g. the “legs”). This has the added benefit of making the bolometer more physically robust. Adjusting the leg geometry (Fig. 1) to maintain a constant saturation power, P, at lower T_c results in an increase in G, because $P \approx G\ T_c/n$, where n is typically $\sim$3. Thus, decreasing the T_c has the additional effect of decreasing the bolometer time constant, $\tau \propto C/G$. This can be compensated for by adding metals to increase the C of the devices.

Previous ground-based and balloon-borne CMB observations using TESes have primarily used ^{3}He sorption refrigerators with bath temperatures in the 0.2 K–0.3 K range and T_c between 0.4 K–0.6 K. We are developing MoCu bilayer TES bolometers with T_c between 0.1 K–0.2 K to take advantage of the performance improvements afforded by lower-T_c devices. The first deployment of these low-T_c bolometers will be on ACTPol [9], which will use a dilution refrigerator (DR) to achieve a bath temperature of $T_b \approx 90$ mK. Future planned deployments include the balloon-borne De-Lensing Inflation by Tomography Experiment (DeLITE), which will be cooled by an

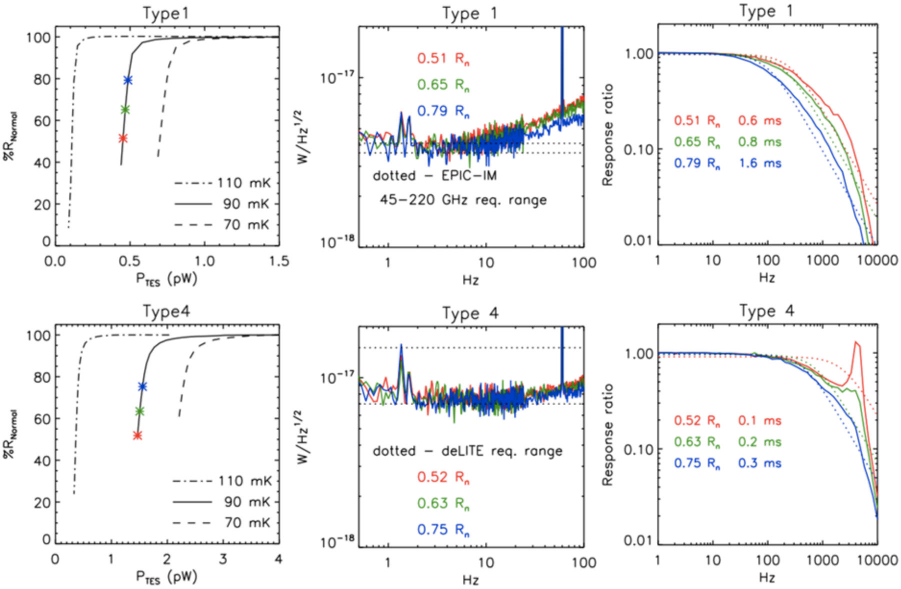

Fig. 2 (Color online) (*top row*) Data from a type 1 bolometer; (*bottom row*) data from a type 4 bolometer. (*left*) $\%R_N$ versus TES bias power, P_{TES}. At lower T_b (see legend) and P_{TES}, the devices have slower time constants and remain stable to lower $\%R_N$. (*middle*) *NEP* at the three bias points (*) indicated on the $\%R_N$ plots at *left*. The type 1 detectors have *NEP* consistent with the requirements for the EPIC-IM 45–150 GHz bands. The type 4 detectors have *NEP* and saturation power that is consistent with the requirements for deLITE. (*right*) Normalized time constant measurements from applying offset sinusoids to the heater lines at different frequencies. Both devices exhibit time constants <0.8 ms, which is sufficient for both experiments

adiabatic demagnetization refrigerator (ADR). This temperature range is also compatible with the EPIC-IM and COrE missions, which would likely use a single-shot DR similar to the refrigerator used on the Planck[1] satellite.

3 Bolometer Measurements and Comparison

We have fabricated prototype bolometers for use on balloon or space missions. Ten different bolometer types were fabricated with $T_c = 117 \pm 2$ mK and G between 10 pW/K–250 pW/K (Fig. 1d), resulting in saturation powers between 0.5 pW–7 pW. The normal resistance, R_N, of these devices is 4.5 ± 1.5 mΩ (limited by uncertainty in the shunt resistor).[2] This resistance is compatible with reading out the devices by use of the well-demonstrated time-division multiplexing [13] (TDM) or next-generation microwave frequency-division multiplexing [14] that use the software-defined radio

[1]For more information about Planck, see: http://www.rssd.esa.int/Planck.

[2]The shunt resistor uncertainty also propagates linearly into the TES power calibrations (Fig. 2), but is substantially smaller than the demonstrated range of saturation power and *NEP*.

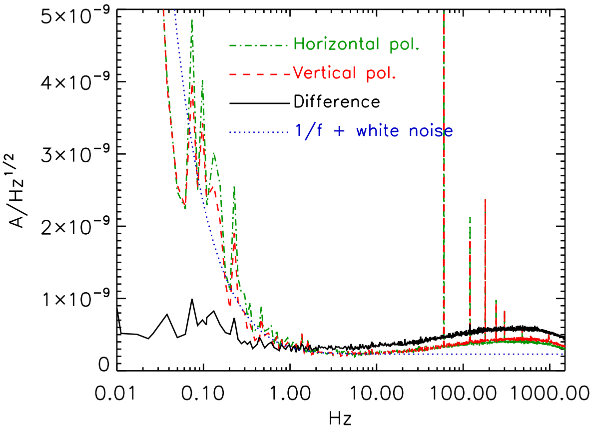

Fig. 3 (Color online) Multiplexed noise spectra from the two bolometers in a polarimeter (*green dot-dashes* and *red dashes*) exhibit $1/f$ with a knee frequency ~1 Hz (*blue dots*). In the differenced polarization channel (*black solid*) the $1/f$ is suppressed to <10 mHz. The 60 Hz and harmonics are also strongly suppressed in the differenced data

readout electronics under development for readout of microwave kinetic inductance detectors.

Detailed measurements of two bolometer types are shown in Fig. 2. These devices demonstrate performance consistent with the requirements for most of the EPIC-IM long-wavelength detectors and the DeLITE detectors. Specifically, the measured type 4 device has noise-equivalent power (*NEP*) $\sim 7 \times 10^{-18}$ W/Hz$^{1/2}$, which is the lowest target noise level for the DeLITE bolometers, and $\tau < 0.3$ ms, which is substantially smaller than necessary. The type 1 device exhibits $NEP \sim 4 \times 10^{-18}$, which is sufficiently low for the longer-wavelength EPIC-IM bands between 45 GHz–150 GHz, and τ between 0.6 ms–0.8 ms near the middle of the transition, which meets or exceeds the time-constant requirements for all EPIC-IM bands. The small bolometer time constants could be problematic, because the response is so fast at lower resistances that the thermal and electrical poles interact, driving the bolometers unstable [10]; however, we have recently demonstrated the ability to tune time constants in higher-saturation-power bolometers for ACTPol by adding PdAu to the bolometer island, and the same approach can be applied here. The additional metal on the bolometer island also appears to improve the bolometer thermalization, which should allow full optimization of the tradeoffs between; stability, minimizing readout noise aliasing, minimizing readout rate (and therefore power consumption), and faster bolometer response.

4 Low-Frequency Noise

Minimizing low-frequency detector noise is essential for maximizing large-angular scale observation sensitivity, especially for balloon and satellite observations where the atmosphere does not contribute significantly. We have measured the dark low-frequency noise of a prototype polarimeter by use of TDM readout. The *X* and *Y* polarization signals were read out as different rows in the TDM circuit with a frame rate of 25 kHz (similar to rates used for ground-based observations with large arrays). To minimize the effect of thermal fluctuations, the bath temperature was set to $\sim T_c/5$. Fourier transforms of the bolometer time streams are shown in Fig. 3. The individual bolometers exhibit a strong $1/f$ component with a knee frequency of $\sim$1 Hz; however, simple differencing of the time streams (as is done for polarization measurements) provides a polarization signal with no evidence of a $1/f$ spectrum to $<$10 mHz, lower than the EPIC-IM requirement of 16 mHz.

5 Conclusions

The silicon feedhorn-coupled TES polarimeters under development by the Truce collaboration are an appealing technology for upcoming balloon-based or space-based measurements of the CMB polarization. We have measured the performance of prototype bolometers that are fully compatible with the Truce polarimeter array technology. The bolometers meet the requirements of the deLITE balloon observatory and the requirements for the EPIC-IM 45–150 GHz bands. We have also demonstrated $1/f$ suppression by pair differencing in a polarimeter to $<$10 mHz, which exceeds the DeLITE and EPIC-IM requirements.

Next steps for further design optimization include adding heat capacity to improve the detector biasing stability and exploring lower saturation power detectors with thinner (0.5–1 µm) SiN membranes to meet the requirements for satellite observations over a wider range of frequencies.

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References

1. CMBpol Mission Concept Study Group and the Primordial Polarization Program Definition Team, CMBpol Mission Concept Study Report for the Astro2010 Decadal Committee on Astrophysics (2009)
2. K. Smith et al., CMBPol mission concept study: gravitational lensing (2009). arXiv:0811.3916
3. J. Bock et al., EPIC-IM Overview. CMBPol Workshop Presentation (2009). http://cmbpol.uchicago.edu/workshops/path2009/abstracts.php#54
4. Cosmic Origins Explorer, European Space Agency White Paper (2011)
5. K.-W. Yoon et al., Feedhorn-coupled TES polarimeters for next-generation CMB instruments. Proc. LTD-13 **1185**, 515–518 (2009)
6. J. Hubmayr et al., An all silicon feedhorn-coupled focal plane for CMB polarimetry. J. Low Temp. Phys. (2012). doi:10.1007/s10909-011-0420-7
7. T. Essinger-Hileman et al., The Atacama B-Mode search: CMB polarimetry with Transition-Edge-Sensor bolometers. Proc. LTD-13 **1185**, 494–497 (2009). arXiv:1008.3915
8. J.J. McMahon et al., SPTpol: an instrument for CMB polarization. Proc. LTD-13 **1185**, 511–514 (2009)
9. M.D. Niemack et al., ACTPol: a polarization sensitive receiver for the Atacama Cosmology Telescope. Proc. SPIE **7741**, 77411S (2010). doi:10.1117/12.857464
10. K. Irwin, G. Hilton, Transition-Edge Sensors, in *Cryogenic Particle Detection*, ed. by C. Enss (Springer, Berlin, 2005)
11. J.P. Nibarger et al., An 84 pixel all-silicon corrugated feedhorn for CMB measurements. J. Low Temp. Phys. (2012). doi:10.1007/s10909-011-0428-z
12. J.J. McMahon et al., Multichroic feedhorn-coupled TES polarimeters. J. Low Temp. Phys. (2012)
13. P.A. de Korte et al., Time-division superconducting quantum interference device multiplexer for transition-edge sensors. Rev. Sci. Instrum. **74**, 3807–3815 (2003)
14. J.A. Mates, The Microwave SQUID Multiplexer. PhD thesis, University of Colorado, Boulder, USA, 2011