J Low Temp Phys (2018) 193:1041–1047
https://doi.org/10.1007/s10909-018-1963-7

The Advanced ACTPol 27/39 GHz Array

S. M. Simon[1] · J. A. Beall[2] · N. F. Cothard[3] · S. M. Duff[2] · P. A. Gallardo[3] · S. P. Ho[4] · J. Hubmayr[2] · B. J. Koopman[3] · J. J. McMahon[1] · F. Nati[5] · M. D. Niemack[3] · S. T. Staggs[4] · E. M. Vavagiakis[3] · E. J. Wollack[6]

Received: 19 October 2017 / Accepted: 10 May 2018 / Published online: 21 May 2018

Abstract Advanced ACTPol (AdvACT) will observe the temperature and polarization of the cosmic microwave background (CMB) at multiple frequencies and high resolution to place improved constraints on inflation, dark matter, and dark energy. Foregrounds from synchrotron and dust radiation are a source of contamination that must be characterized and removed across a wide range of frequencies. AdvACT will thus observe at five frequency bands from 27 to 230 GHz. We discuss the design of the pixels and feedhorns for the 27/39 GHz multichroic array for AdvACT, which will target the synchrotron radiation that dominates at these frequencies. To gain 35% in mapping speed in the 39 GHz band where the foreground signals are faintest, the pixel number was increased through reducing the pixel diameter to 1.08λ at the lowest frequency, which represents a 22% decrease in size compared to our previously most tightly packed pixels.

Keywords Cosmic microwave background · Advanced ACTPol · Atacama Cosmology Telescope · Synchrotron · Foregrounds · Multichroic pixel · Detector design · Polarization-sensitive detector · Transition-edge sensor

✉ S. M. Simon
smsimon@umich.edu

1 Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA

2 Quantum Sensors Group, NIST, Boulder, CO 80305, USA

3 Department of Physics, Cornell University, Ithaca, NY 14853, USA

4 Department of Physics, Princeton University, Princeton, NJ 08540, USA

5 Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, PA 19104, USA

6 NASA/Goddard Space Flight Center, Greenbelt, MD 20771, USA

1 Introduction

AdvACT is an upgraded camera for the Atacama Cosmology Telescope that will measure the CMB in both temperature and polarization over a wide range of angular scales and five frequency bands from 27 to 230 GHz with unprecedented resolution and sensitivity. AdvACT's sensitivity, resolution, wide frequency coverage, and large sky coverage will enable it to simultaneously probe inflation at large angular scales while using small angular scale measurements to constrain the mass and number of neutrino species, dark energy, and dark matter [1]. CMB polarization measurements are contaminated by galactic foregrounds from dust and synchrotron emission, so wide frequency coverage is required to characterize and remove these signals [2]. AdvACT has deployed one high-frequency (HF) 150/230 GHz and two mid-frequency (MF) 90/150 GHz feedhorn-coupled, polarization-sensitive multichroic pixel arrays in its three optics tubes. The final low-frequency (LF) 27/39 GHz AdvACT array will take the place of one of the MF arrays upon its deployment in 2018. The AdvACT LF array will consist of 73 multichroic pixels that will measure the synchrotron foregrounds, which are dominant at lower frequencies, with unprecedented sensitivity and resolution, making it singular in the field. We present the design of the pixels and feedhorns for the AdvACT LF array.

2 27/39 GHz Pixels for AdvACT

The AdvACT LF array will target the synchrotron foregrounds with two bands ranging from 24–30 GHz and 30–48 GHz. This will be the highest resolution, sensitive ground-based CMB camera covering these frequencies to date. The AdvACT array layout consists of three rhomboid sections of $n \times n$ pixels for a total of $3n^2$ pixels fabricated on a 150 mm wafer. In every configuration, two pixels are lost to make room for mechanical components. Two array configurations that fully fill the available array area were considered for the LF array: a 13.4 mm pixel pitch with 73 pixels and a 16.1 mm pixel pitch with 46 pixels. Simulations show that the 13.4 mm pixel size results in mapping speed gains of 23 and 35% for the 27 and 39 GHz bands, respectively. The AdvACT LF array thus has 73 feedhorn-coupled 13.4 mm pixels. A 13.4 mm pixel is 1.08λ at 24 GHz. This poses several design challenges, which are described in this section.

A prototype LF pixel is shown in Fig. 1. Light from each feedhorn is waveguide-coupled to a planar orthomode transducer (OMT) on a relieved SiN_x membrane that splits the radiation into two orthogonal polarizations. The signal is then routed via superconducting Nb microstrip lines to a diplexer realized from quarter-wave stub filters to define the bandpasses, a hybrid tee for mode selection, and onto a microwave termination for detection by a transition-edge sensor (TES) bolometer. Each of the two frequency bands on each pixel has three TES bolometers, a dark bolometer and one for each orthogonal polarization.

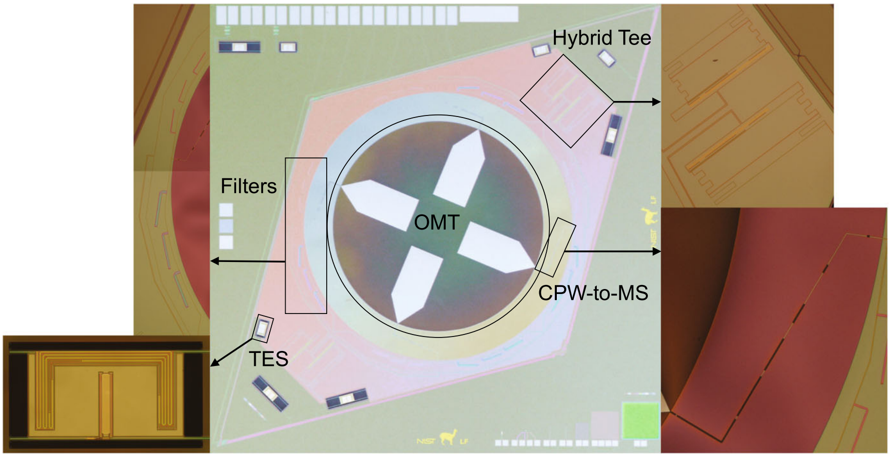

Fig. 1 A prototype LF pixel is shown. Light is coupled through the 7.8-mm-diameter OMT then travels through a CPW-to-MS transition, band-defining filters, a hybrid tee, and onto the TES. Each pixel has a total of six TESes, four of which are optically coupled. Photographs courtesy of Dan Schmidt and Shannon Duff (Color figure online)

2.1 Coupling Light onto the Pixel

Light is coupled onto the pixel by a feedhorn that ends in a waveguide. To separate the incident polarizations and impedance match the signals presented by the waveguide, pairs of OMT antenna probes on the SiN_x membrane are connected to coplanar waveguide (CPW). The waveguide terminates in a quarter-wave backshort after the OMT membrane. There is a 25 µm discontinuity in the waveguide above and below the pixel for mechanical purposes that, coupled with the need for the CPW, necessitates an extra diameter of relieved membrane. If the OMT and extra relieved membrane designs are frequency scaled from the MF array, the result is a 7.8-mm-diameter OMT with a 12.7-mm-diameter extra relieved membrane. To enable the 13.4 mm pitch, the size of the extra relieved membrane needed to decrease. Fortuitously, the low frequencies of these pixels are less sensitive to the waveguide discontinuity than the MF array, and the extra membrane diameter can thus be decreased to 10 mm with negligible impact on the performance. The OMT response coupled to a feedhorn is shown in the left panel of Fig. 2.

2.2 CPW-to-Microstrip Transition

The next component in the pixel is an impedance-matching transition from the CPW to the microstrip (MS) used for the on-chip circuitry. The nominal frequency-scaled design for this component has a single 90° bend, but the smaller diameter of the extra relieved membrane necessitated more bends to fit the component. A CPW-to-MS transition with three bends was modeled, but it had significantly increased reflection, so the final design uses a transition with two bends that recovers almost the full

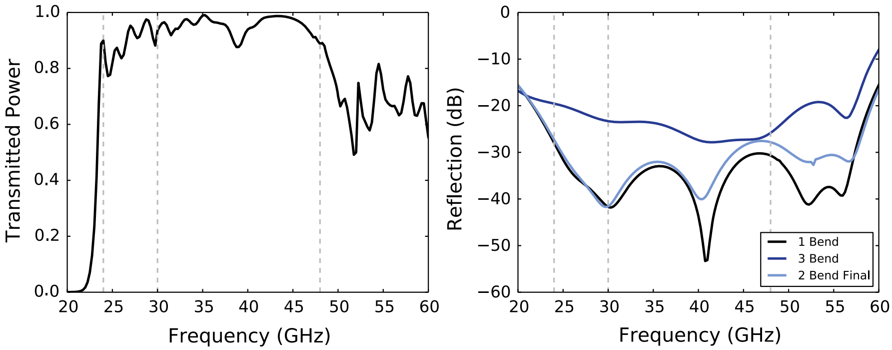

Fig. 2 Left: the transmission of the OMT coupled to a feedhorn. Right: the reflection of the CPW-to-MS transition is shown for the 1 bend (black), 3 bend (dark blue), and final 2 bend (light blue) designs. The 2 bend reflection is similar to that of the 1 bend design, while the 3 bend design has significantly more reflection. The vertical dashed lines indicate the band edges (Color figure online)

performance of the single bend design. The reflections of these three designs is shown in the right panel of Fig. 2.

2.3 Filters

AdvACT employs diplexers with quarter-wave stub filters to define the bandpasses of the dichroic pixels. Both the HF and MF designs use 5-pole filters [3]. A 5-pole LF filter has a length of 7941 µm, which is too large to fit on a 13.4 mm pixel. Thus, a 3-pole filter with a total length of 4688 µm is used. The 3-pole and 5-pole filters designed for the LF pixels are plotted together in the left panel of Fig. 3. The upper edge of the high frequency band rolls off more slowly for the 3-pole filter, but this is mitigated by the OMT cutoff and a planned free-space low-pass filter placed above the detector array. The low edge of the low band is further defined by the feedhorn waveguide cutoff. Unlike the MF and LF bands, there is no separation between the upper and lower bands because there are no atmospheric lines to avoid. To further compress the filter size to fit on the pixel, each stub is bent at a 90° angle, and the full diplexer is curved around the membrane. The effects of these modifications on performance are small and are shown in the right panel of Fig. 3.

2.4 Hybrid Tee

For each frequency and polarization, a hybrid tee is used to combine the signals from the pair of OMT coupling probes to define the polarization and exclude higher-order modes. The straight sections of the hybrid tee are meandered to make the components more compact, which has a negligible impact on the performance as shown in Fig. 4.

2.5 TES Bolometer

There is another impedance transition between the MS and the lossy Au on the TES island. The TES bolometers on the LF array are designed for a critical temperature of

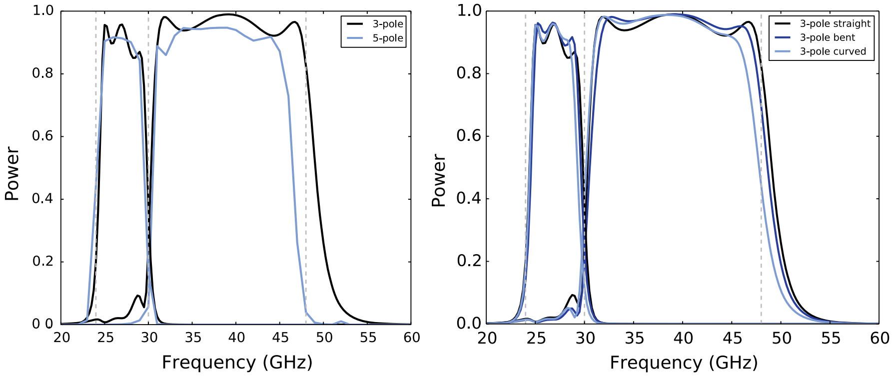

Fig. 3 Left: the response of the 3-pole (black) diplexer versus the 5-pole diplexer (light blue). The 3-pole filter is more compact, but has a more gradual band edge at $\sim$ 48 GHz. Right: the responses of the 3-pole diplexer with straight stubs (black), after bending the stubs (dark blue), and after curving the bent stubs (light blue) are shown. The signal slightly decreases at higher frequencies after curving the diplexer due to reflections off of the bends. The vertical dashed lines indicate the targeted band edges (Color figure online)

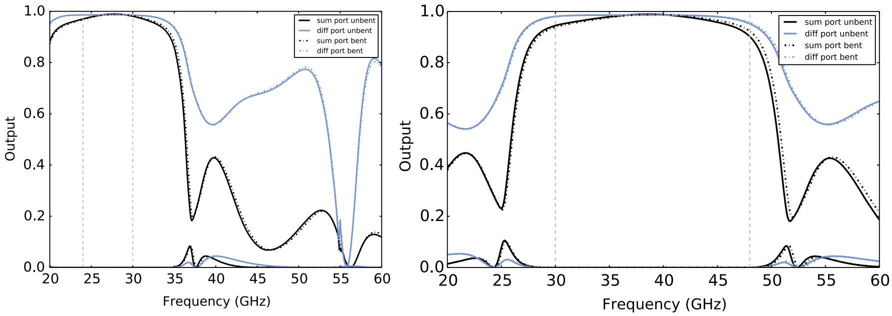

Fig. 4 The sum (black) and difference (light blue) port responses of the hybrid tee are shown for the 27 GHz (left) and 39 GHz (right) bands. The solid lines are the unbent hybrid responses, while the dashed lines show the bent hybrid responses. The change is negligible (Color figure online)

165 mK. Because the expected sky loading is only 0.5 pW in the 27 GHz band, the TES is designed for 1.5 pW of loading, which results in 10 µm by 628 µm TES legs. More details on the design and selection of the TES properties can be found in the proceedings from Koopman et al. in this edition [4]. The full pixel response from the OMT through the hybrid tee is shown in Fig. 5.

3 Feedhorns for the LF Array

The AdvACT arrays employ spline-profiled feedhorns for their good beam symmetry and efficiency while maintaining a small footprint. The LF feedhorns (Fig. 6) are designed through the Markov chain Monte Carlo optimization described in Simon et al. [5]. Their beam coupling efficiency is 33% in the low band and 53% in the high band with band-averaged cross-polarizations of 0.88 and 0.93%, respectively. Unlike the MF and HF arrays which are made from stacked Si wafers, the LF arrays are direct

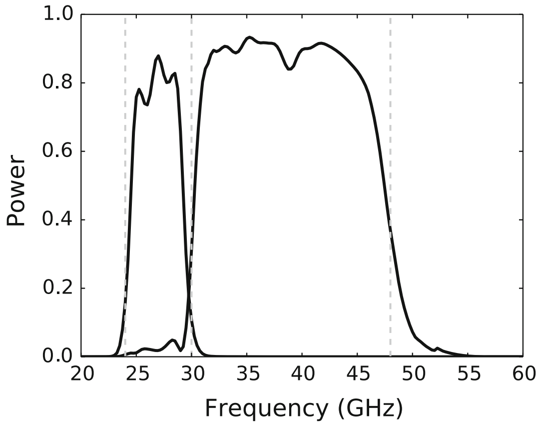

Fig. 5 The full detector response including the OMT, CPW-to-MS transition, filters, and hybrid tees is shown. The vertical dashed lines indicate the targeted band edges. Note that a free-space filter in the telescope optics that is not modeled here provides further attenuation of frequencies above 48 GHz

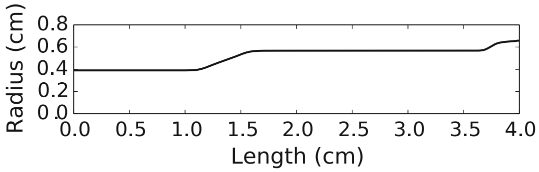

Fig. 6 The profile of the AdvACT LF spline-profiled feedhorn is shown. The total length of the feedhorn is 4 cm. Spline-profiled horns exhibit good beam symmetry and beam coupling efficiency for their compact size

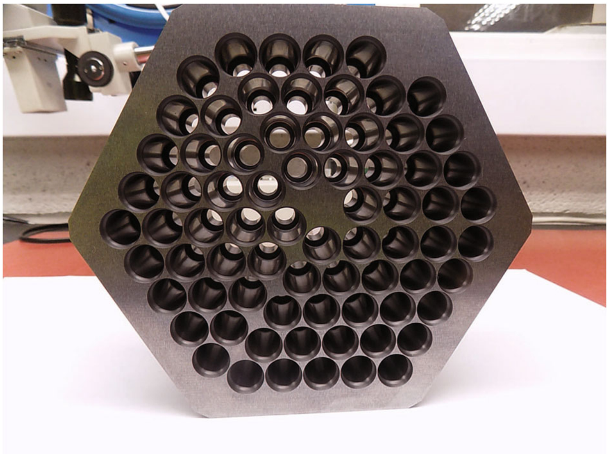

Fig. 7 The full LF AdvACT feedhorn array prior to gold coating. The array is direct machined out of a Si–Al alloy (Color figure online)

machined into CE7F, which is a lightweight Si–Al alloy with a coefficient of thermal expansion close to that of Si. This method is less expensive and allows for a smoother profile. After machining, the feedhorn array is coated in gold for thermalization and cooling [6]. The full feedhorn array before gold coating is shown in Fig. 7.

4 Summary

The 27/39 GHz AdvACT array consists of 73, 13.4 mm pixels and will field in 2018, producing the highest resolution, sensitive maps at these frequencies to date. Compressing the LF pixel size has allowed for an increase in the number of pixels by a factor of 1.6 and thus a gain in mapping speed of 23% in the 27 GHz band and 35% in the 39 GHz band. We have modeled the effects of shrinking pixel components to achieve this small pixel size and find them to be minimal. The LF array will employ direct-machined feedhorns with a new Si–Al alloy, reducing the cost and lead time of production, which is a critical step for future projects like Simons Observatory and CMB-S4.

Acknowledgements This work was supported by the US National Science Foundation through Award 1440226. The development of multichroic detectors and lenses was supported by NASA Grants NNX13AE56G and NNX14AB58G. The work of BJK was supported by NASA Space Technology Research Fellowship award.

References

1. S.W. Henderson et al., Proc. SPIE **9914**, 99141G (2016). https://doi.org/10.1117/12.2233895
2. M. Tucci et al., Mon. Not. R. Astron. Soc. **360**, 935 (2005). https://doi.org/10.1111/j.1365-2966.2005.09123.x
3. R. Datta et al., J. Low Temp. Phys. **176**, 670 (2014). https://doi.org/10.1007/s10909-014-1134-4
4. B.J. Koopman et al., J. Low Temp. Phys. (2018). https://doi.org/10.1007/s10909-018-1957-5
5. S.M. Simon et al., Proc. SPIE **9914**, 991416 (2016). https://doi.org/10.1117/12.2233603
6. T. Essinger-Hileman et al., Proc. SPIE **9153**, 91531I (2014). https://doi.org/10.1117/12.2056701