Chapter 9

Conclusions and Future Work

9.1 Introduction

This concluding chapter discusses the next steps that need to be taken in this on-going project. Correcting the beam asymmetries is of paramount importance. We suggest two possible solutions to address this challenge.

We have also delayed a discussion of potential advantages this technology may offer over competing detectors until this final chapter so we can use results from previous chapters. We take up this topic in this final chapter as well.

9.2 Status of work

We argued in chapters 1 and 2 that there is compelling science in CMB B-mode searches and that the faint B-mode signal masked by galactic foregrounds requires high optical throughput through multiple colors. Historically, required increases in sensitivities have been driven by advancements in detector technology, and we hope to continue this trend with log-periodic pixel designs.

Log-periodic antennas and circuits achieve high bandwidth through their self-similar design, and we have demonstrated that the sinuous antenna has desirable properties. It
has high optical throughput in both linear polarization channels with circular beams and high cross-pol rejection. It can couple to TES bolometers through planar microstrip circuits, so it can be scaled to large arrays. When driven with a properly balanced feed, the beam properties show rough agreement with beams simulated in ADS and corrected with a raytracing script.

Additionally, we have demonstrated that we can partition this bandwidth into narrow frequency channels in planar microstrip circuits, also with high throughput. The diplexers and triplexers (chapter 7), allow band placement between atmospheric lines and is best suited to a terrestrial experiment. The log-periodic circuit (chapter 8) has several adjacent channels and may be advantageous for a satellite mission.

We have also made an initial demonstration of a multi-layer anti-reflection coating for the contacting lenses. These coatings were realized with the commercially available material TMM. They increased the optical throughput as much as 30% and retained beams that were similar to those through quarter-wavelength coatings.

The last outstanding issue with these pixels is the beam asymmetry in the channelized pixels. These problems were likely created by the feed design and we are pursuing schemes to correct this.

### 9.3 Correcting the beam asymmetries with a balun

#### 9.3.1 A Dyson balun

The differentially fed resistive loads on the bolometers of chapter 6 reject 100% of the even mode and only terminate the odd mode. Provided that the transmission lines and filters between the antenna and termination are identical, the pixel is guaranteed to have a centered beam that is symmetric around the axis between the two opposite arms. The beams of chapters 7 and 8 clearly lack this desired symmetry and we hypothesize that this occurred because the antenna was not fed with a properly balanced feed; the currents on opposite arms were not forced to be identical.
One possible solution is to add another cell to the antenna’s interior and to keep the ground plane as narrow as the microstrip’s upper conductor width at the feed point. These changes would help ensure that both conductors of the transmission line appear identical to the antenna at the feed and thus that the antenna arms are fed identically. The ground plane then gradually widens as the feed lines wind outward. This feed is very similar to the Dyson balun was originally implemented with coax-cable soldered to the back of two armed log-spiral antennas (Dyson [1959]). Nurnberger and Volakis [1996] have since used this scheme to feed a two-armed arithmetic-spiral antenna with microstrip in a manner similar to our attempted feed.

There is room for an additional cell in the interior of the antenna; in fact the antennas in chapter 6 had this additional cell. The simulations of the antenna with these two feed corrections are encouraging (see Figure 6.11). However, the simulations of the antennas in chapters 7 and 8 looked far better than the measured results, so there may be systematic effects not reflected in these simulations.

9.3.2 CPW to reject an even-mode

A more aggressive solutions feeds the antenna differentially (two lines per polarization) as in chapter 6, but using a lithographed circuit that itself ensures rejection of the even mode before channelizing. An ideal circuit would be a broadband directional coupler. These circuits can combine incident waves from two input ports into sum and difference modes and can be made with multiple sections to achieve a decade band-width. Engineers prefer these circuits for this application because they can resistively terminate the sum port (even mode) instead of reflecting it away, leaving absolutely no question as to where power in this unwanted mode goes.

Unfortunately, we have not succeeded in designing these circuits in either microstrip or CPW. The currents in the two microstrip upper conductors of a directional coupler can be expressed as a combination of even and odd modes, where the even mode has equal currents in the two coupled conductors, while the odd mode has equal but opposite currents (These
modes are distinct from the antenna’s even and odd modes). To mix the two input signals with even weight, the capacitive coupling between the lines must be much larger than the shunt capacitance to ground and the even and odd-mode wavespeeds between the coupled line must be well matched. However, these lines are quasi-TEM, as discussed in Chapter 6, so the two wavespeeds are not well matched. This greatly degrades the coupler’s balance and phase stability. The thin dielectric film also precludes strong capacitive coupling between microstrip lines.

![Diagram of a slot-line balun](image)

**Figure 9.1.** Un-tested Slot-line balun that divides power from port 1 evenly between ports 2 and 3 with a 180° phase shift.

We have alternatively designed a circuit that couples signal on microstrip from each arm onto a slot-line with electrically-open ends. We then couple the summed power onto a third microstrip in the center. Figure 9.1 shows a fabricated slot balun that we never tested because of a fabrication error. If the input lines cross the slot from opposite sides, then the desired odd-mode will constructively interfere at the center microstrip while the even mode will destructively interfere at that point. Slotlines have been used as inverters in microwave applications and this design is similar in spirit. The undesired even-mode reflects back to the antenna, making it electromagnetically similar to the Polarbear feed discussed in chapters 4 and 6.
Slot-lines can radiate; in fact, the Polarbear crossed double slot-antenna is a set of slot-lines that efficiently radiate. By curving the slot-line into a horse-shoe, the line is similar to a short stretch of low-impedance CPW. As a result, some components of the far fields destructively interfere to reduce the radiated power. With this geometry, the input impedance is $38 \, \Omega$ and the radiated power is 3% (See figure 9.2). Currently, the line length is $\lambda/8$ long at 220GHz, which is why it begins to radiate and decreasing this length should further suppress this, but the shorter lines also have higher impedances at the ports. We would like to reduce the radiation below 1% with useable impedances and further work is needed to realize this.

![Simulated Scattering parameters of the proposed balun circuit with each port terminated with $38 \, \Omega$.](image)

Figure 9.2. Simulated Scattering parameters of the proposed balun circuit with each port terminated with $38 \, \Omega$. $|S_{12}|$ and $|S_{11}|$ are well matched, but the downward slope shows a slight radiation of about 3% at 225GHz. This needs to be reduced to less than 1% before the balun will be acceptable.

Finally, feeding the antenna with two arms instead of one resolves the challenge of matching the microstrip impedance to the high impedance of the antenna. If the lines feed the antenna in the H-V excitation, then there will be a virtual ground at the center and each arm will only need to match to $52 \, \Omega$ instead of the much higher $104 \, \Omega$ of the feeds discussed in chapters 6-7 (See Figure 9.3). This feeding scheme was only recently realized by our UCSD collaborators and if it is necessary to feed each polarization with two lines, this is clearly the most promising way to optimize the impedance match.
Figure 9.3. A balanced H-V feed where each arm will only see 52 Ω relative to the virtual
ground at center. One polarization is grayed out and the antenna current is shown in the
blue arrows. This is photo-shopped for purposes of explanation - we have not fabricated it yet.

9.3.3 Differentially-fed terminations

In principle, we could channelize the signal from each arm first and then differentially
feed the termination as in chapter 6. This solution is undesirable because it would involve
excessive microstrip crossovers as well as microstrip-bias line crossovers. Additionally, it
requires that the channelizer circuits on each arm be identical; any differences will steer the
beam from center or cause one arm’s band to shift relative to the other. This is especially
worrisome because the footprint of the multi-channel devices is much larger than the single
channel Polarbear devices and the films must be uniform on this large area. With any of
these defects, the antenna would couple to the even mode. We have seen some evidence
of this problem in some of the Polarbear pixels as well. Additionally, the detectors from
Caltech/JPL that couple through large antenna arrays have experienced beam steer which
they attribute to non-uniform film properties.
9.4 Comparison of Log-periodic detectors to competing technology

After the success of the devices described in chapter 6, we are optimistic that we can suppress the beam asymmetries in the sinuous antenna. Once that final challenge is met, this device will be competitive with other currently deployed or deploying technologies. In this section, we describe how we envision constructing a focal plane with these pixels and then compare how it would compete against existing technologies.

9.4.1 Relative Mapping speeds

The signal-to-noise ratio of a measurement is

\[
\text{snr} = \frac{P_s \sqrt{\tau}}{\text{NEP}}
\]  

(9.1)

where \( \tau \) is integration time, \( P_s \) the signal power, and if the measurement is background noise limited, then \( \text{NEP} \propto \sqrt{P_s} \) (Griffin et al. [2002]). The mapping speed quantifies how quickly a target signal to noise at a given point on the sky can be achieved and goes as \( \text{Speed} \propto N \text{snr}^2 \) (Griffin et al. [2002]), where \( N \) is the number of pixels in a focal plane. All of the polarized CMB anisotropies that we intend to map will be much larger than the beam. In this limit,

\[
\text{speed} \propto \frac{N \eta_S^2}{\eta_S B_{\text{ext}} + (1 - \eta_S B_{\text{int}})}
\]  

(9.2)

\[
\propto N \eta_S
\]  

(9.3)

where \( B_{\text{int}} \) and \( B_{\text{ext}} \) are the internal and external brightness and \( \eta_S \) is the spillover efficiency- the fraction of the pixels’ power that couples to the telescope’s primary diffraction limiting optic Halverson [2004]. In many applications, this efficiency is set with a cold aperture stop so the spillover can be terminated on a surface of known and controlled
temperature. The last line applies to a camera where the stop is chilled to millikelvin temperatures \( B_{int} \ll B_{ext} \).

In all of these calculations, we compare the mapping speeds in specific channels between two instrument designs. Clearly, optimizing a deploying experiment would involve weighting each of the spectral channels to reflect their astrophysical importance. However, the preferred weights will likely shift as Plank and the next generation of experiments learn more about the galactic foregrounds. Instead, we only seek to quantify the potential gains that this technology offers over traditional focal-planes in a “toy-calculation” where we weight the value of every channel evenly.

### 9.4.2 Proposed Focal-plane design

Chapter 4 discusses how an antenna radiating a wavelength \( \lambda \) under a contacting synthesized ellipse with radius \( R \) has a beamwidth that scales as \( \lambda/R \). Data from chapters 7 and 8 corroborate this model. Since the beam size changes with channel, the pixels can only have an optimal \( 2f\lambda \) spacing at one frequency. Several experimenters mapping extended sources choose to space the pixels at \( 2f\lambda \) because it results in high spillover efficiency and high pixel density.

We envision designing a focal plane with \( 2f\lambda \) spacing at the highest channel for a camera with a cold stop that terminates this beam at the -10dB contour. For the triplexer or log-periodic channelizers discussed in previous chapters, this occurs at roughly 225GHz, or 1.3mm in free space. The longer-wavelength beams will be wider and will spill onto the stops at higher powers contours. However, the pixels receiving in these longer wavelength channels will be denser than a monochromatic array with \( 2f\lambda \) spacing, which roughly compensates for the power lost to the stop. But if there are N channels in the telescope, then focal planes with multichroic pixels will provide an additional factor of N in mapping speed over a system with monochromatic pixels. This simple fact yields a dramatic boost in mapping speeds, and we quantify this in Figures 9.4 and 9.5. In these charts, we compare our proposed design against a multi-channel telescope where the focal plane is partitioned into
large sections with monochromatic pixels spaced at $2f\lambda$ (e.g. EBEX). Alternatively, the telescope could have multiple cameras with monochromatic $2f\lambda$ focal planes where each camera is dedicated to one of several frequencies (e.g. SPIDER). These architectures are commonly used in most contemporary telescopes.

![Graph](image)

(a) 90-150 Diplexed Pixels

![Graph](image)

(b) 90-150-220 Triplexed Pixels

Figure 9.4. Array parameters relative to a $2f\lambda$ monochromatic array. Each channels’ speed gets a boost of a factor of 2 (figure a) or 3 (figure b) because there are respectively 2 or 3 channels per pixel.

Several terrestrial CMB-polarization experiments have deployed recently or will deploy over the next year with antenna-coupled TES bolometers. These include BICEP-2, Keck Array (formerly SPUD), Polarbear, and SPT-pol. All of these experiments plan to receive multiple frequency channels at combinations of 90, 150 and 220GHz band-centers. But with the exception of Polarbear, they will use monochromatic pixels. If these experiments were upgraded to 2-3 channel pixels, these experiments could achieve mapping speed gains roughly equal to those in Figure 9.4.

This increase in throughput clearly comes at the cost of more required read-out channels.
Several groups are developing microwave frequency (1-10GHz) SQUID multiplexing that may dramatically increase the number-count of TES focal planes. Alternatively, MKIDs naturally down-convert to microwave frequencies when multiplexing and may be a viable replacement to TES bolometers in the future.

Recent advancements in MKID technology have shown that the white noise dominated by two-state transitions varies strongly with the electric fields strength, and they have suppressed that noise by building resonators with inter-digitated capacitors instead of lumped MIM capacitors. While this changed allows for background limited measurements, the footprint of the detector is sufficiently large that it drastically reduces the useful focal-plane real-estate in antenna array-coupled pixels. The detector architecture described in this thesis would naturally allow the bulky MKID resonator hide under he contacting lenses, dramatically boosting the packing density while still maintaining the wide bandwidth.

9.4.3 Application in a Satellite Mission

Satellites experiments do not have to avoid atmospheric lines and can receive contiguously placed channels. Current CMB satellites include WMAP and Plank, but their focal planes use technology that is not as scalable as lithographed TES arrays and do not make for a useful comparison. Alternatively, balloon-bourn experiments are often a demonstration of technology for future space missions, and two such modern experiments are EBEX and SPIDER. They will both have between 1000 and 2000 pixels spanning 1.5 octaves, although SPIDER will be dual polarized. These experiments still position band-centers between atmospheric lines to reduce external loading, but if orbital versions are made, they can place bands arbitrarily. Table 9.5 shows how a SPIDER or EBEX-like satellite experiment would benefit from a multi-chroic upgrade.

Figure 9.5 shows that multi-chroic pixels can significantly boost the throughput for a focal plane of fixed size. Alternatively, the multi-chroic pixels could reduce the physical size of a camera for a fixed target speed. Since both Plank and WMAP have utilized multiple channels over a two octave bandwidth, log-periodic pixels would be a viable architecture
that would decrease the size by a similar factor of 7-10. Since the cost of satellite missions often scales with weight of the payload, this can dramatically the cost of satellite missions. Low cost alternatives like this may be necessary to secure funding for future B-mode search satellites.

9.5 Future Work

We plan to upgrade the single-channel pixels for the Polarbear focal plane to multi-channel pixels at some point in the future. The first stage of upgrade will replace the crossed-double slot with the sinuous but with only one channel behind it. This will provide an opportunity to study the sinuous beams through the entire telescope without the added complications of extra channels. The next fabrication will have antennas with a properly implemented balun, but if that does not provide adequate beams, an additional fabrication could produce an array of dual-polarized versions of the Chapter 6 pixels, differentially feeding the lumped terminations at the bolometers. This geometry will require a microstrip cross-over, but this has already been successfully demonstrated with the current Polarbear focal plane.

Polarbear-2 will upgrade the current single color camera to one with a focal plane of
90-150 diplexers. This is the simplest possible upgrade with nearly acceptable beams as currently implemented. Such an upgrade will increase the throughput by a factor of roughly 2 while allowing for the control of one foreground. To utilize such a pixel, the rest of the optics, such as the HDPE lenses and waveplate, must be made comparatively broad-band, and our collaborators at KEK are pursuing many of these challenges.