Multi-band Dual-Polarization Lens-coupled Planar Antennas for Bolometric CMB Polarimetry

Adrian T. Lee

Department of Physics, University of California, Berkeley CA 94720
Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720

E-mail: `Adrian.Lee@berkeley.edu`

Abstract. Len-coupled planar antennas provide a means to efficiently utilize the focal-plane area of a CMB polarization telescope. Our current pixel designs sense both linear polarizations and multiple photometric bands with an overall bandwidth ratio of 3:1. Planar RF channelizing filters distribute power to two bolometers for each frequency band, one for each polarization. Compared to a focal-plane of single-band pixels, the use of these multi-band pixels allow some combination of lower size/mass, larger frequency range, more frequency bands, and higher overall sensitivity. The detector wafer is fully lithographed, and the contacting hemispherical lenses that are required for each pixel are positioned using a second lithographically defined wafer. We have developed a multi-layer broad-band antireflection coating for the lenses. We have tested a superconducting prototype with two polarizations and frequency bands at 150 and 220 GHz, and we have performed accurate beam pattern measurements using scale models at room temperature. To demonstrate this technology at NASA TRL-5, a laboratory demonstration of a full-featured pixel including beam patterns, optical efficiency, band shape, and polarization performance is required, followed by the use of such a pixel in a sub-orbital experiment.

1. Introduction

A dedicated CMB polarization mission, such as CMBPOL, will require high overall sensitivity and a broad frequency range with 5-10 or more photometric frequency bands to characterize and subtract foregrounds. Since bolometers operated at temperature < 250 mK are near the sensitivity floor set by photon counting statistics, the overall sensitivity will be given by the number of detectors, assuming that each detector detects a single-mode to get the highest possible angular resolution. In the current EPIC-JPL concepts, for example, a combination of sufficient frequency bands and a high detector count are achieved using six 30 cm aperture telescopes with seven total bands or one 1.5-3 meter aperture with eight bands. Total optical throughput, and therefore the possible number of single-mode detectors, increases with aperture size in addition to increasing angular resolution, but obviously at the cost of size and weight.

Given the need for a high product of band number multiplied by detector number, it is very advantageous to have a pixel that can detect more than one band simultaneously. We are developing a pixel architecture that can sense two linear polarizations and multiple photometric frequency bands simultaneously. Such a design can greatly reduce the mass of the experiment while holding the detector and band number constant. For example, it may be possible to achieve the required total sensitivity and band number with a single 30-50 cm diameter reflective or refractive telescope.

2. Lens-Coupled Planar Antennas

In general, planar antennas use elements that have a length comparable to the wavelength of the radiation detected. For "resonant" antennas, the length of the antenna is often 1/4, 1/2, or 1 λ. For log-periodic antennas, which will be discussed below, the antenna is made up of "arms" that vary in length such that some part of the antenna is resonant over a broad range of wavelengths.

An antenna that is comparable in length to the wavelength will have a very broad antenna pattern, since the antenna pattern is essentially set by diffraction and $\theta_{beam} \sim \lambda/length \sim 1\ radian$. To increase the directivity of an antenna, many wavelength elements can combined into a "phased array" or the antenna can be placed behind a lens in direct contact with the antenna. The presence of a high dielectric constant silicon lens means that 90% of the power is received from the front. Lens-coupled planar antennas were developed by the antenna-engineering community and they are commonly used there. In astrophysics, they have been used for coupling to SIS mixers, for example, by the Zmudzinas group[1].

Before working on the multichroic antenna, we developed an antenna-coupled bolometer using the well characterized double-slot dipole design [1]. We integrated the antenna with band-defining planar filters and Transition-Edge Sensor (TES) bolometers [2]. We have been able to demonstrate $\sim$ 35% receiver optical efficiency, a band-pass consistent with design, and an upper limit on main-beam cross-pol of 2%. The optical efficiency would improve to $>$ 40% by adding an antireflection coating on the contacting silicon lens. A focal plane of 644 such pixels (1288 bolometers) will be fielded on the POLARBEAR experiment in 2009/2010.

3. Log-Periodic Antennas

Planar dipole antennas have less than 40% fractional bandwidth over which the impedance match offers better than -10dB return loss[1]. The bandwidth where the beam has usable properties is often smaller. Log periodic antennas offer a much wider bandwidth because they are self-similar. They are composed of repeating geometrically-similar resonant sections known as cells that differ in size from their neighbors by a common factor τ, typically between 1 and 2. As a result, the antenna impedance and beam-properties are identical for frequencies whose logarithm differ by $\ln(\tau)$ and vary marginally for frequencies within a log-period [3]. The bandwidth of these antennas is only limited by the size of the smallest and largest log-periodic cells.

The plane of linear polarization of a log-periodic antenna will rotate periodically as the excited region moves from cell to cell. The amplitude of this polarization rotation can be controlled by the design of the antenna. As discussed below, we have created a design with a 5^o amplitude polarization rotation, and this level of wobble can be mitigated by accurate calibration of the polarization angle for each frequency band.

4. Lens-Coupled Sinuous Antenna

The sinuous antenna (Figure 1) is a log-periodic antenna that has been known for useful polarization properties since DuHamel invented it in the 1980s [4]. The edges of the switch-backing arms follow the equation [5]:

$$\phi = \alpha \sin \frac{\pi \ln(r/R_o)}{\ln \tau} \pm \delta \qquad \text{for } R_o < r < R_o \tau^N \tag{1}$$

Each of the four arms snake through an angle of $\pm\alpha$ every rescaling of τ^2. Typical values of α are between 30^o and 70^o , while typical values of τ are between 1.2 and 1.5. The standard log-periodic antenna has a radial metal arm with azimuthal "teeth" connected to the arm. In the sinuous, by contrast, the antenna is formed from a continuous winding structure.

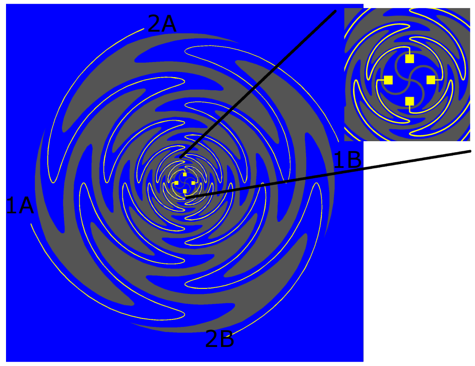


Figure 1. Drawing of a sinuous antenna. This antenna is designed to be placed in contact with a half-space of silicon and to be driven with oppositely phased currents on the microstrip lines (yellow) that couple to the slots (gray) in the center. The polarization of this antenna rotates $\pm 4.5^o$ as a slowly varying function of frequency.

5. Telescope Coupling and Mapping Speed

The antenna gain of the lens-coupled sinuous antenna varies with frequency. In the reverse time sense, the entire lens can be considered a constant-size transmitting surface for all frequencies with diffraction then determining the antenna gain. As the antenna gain varies, so will the the fraction of power that "spills over" the primary aperture (again in the reverse time sense), and therefore the lens-coupled sinuous antenna will require an aperture stop at sub-Kelvin temperature to avoid sensitivity degradation due excess loading and photon-noise from the aperture stop. A trade-off analysis of pixel NET versus antenna-gain has been done by Griffin et al. for pixels with a single-frequency band[6], and it can be applied to the multichroic pixel by calculating the sensitivity at each frequency band for a fixed lens size. Assuming an aperture stop temperature of 500mK, such that power from the sky is 1000 times higher than power from the aperture stop, the sensitivity of a 3:1 ratio bandwidth pixel is within 15% of an optimized single-frequency array at all frequencies. A further improvement can be made by phase arraying of the pixels, including lenses, where the number of pixels that are phased together scales with frequency such that the antenna gain stays roughly constant.

6. Measured Beams of Scale Models

After detailed electromagnetic simulations, we built and tested a 3-12 GHz scale model. The availability of low-cost microwave hybrids, standard gain horns, and network analyzers allow for far easier testing than would be possible with mm-wavelength antennas.

The tested antenna was a wire (non-slot) version instrumented with chip diode detectors mounted across opposite arms in the center. We used a scale model of the contacting silicon lens made from Emmerson-Cuming Microwave Eccostock HiK 12 material, chosen because its dielectric constant of $\epsilon = 12$ closely matches that of silicon. The lens consisted of a 6 inch diameter hemisphere and a 1.5 inch extension block.

Beam maps of this diode-fed antenna were measured in an anechoic chamber and are shown in Fig. 3. The beam maps are largely gaussian in shape, symmetric, and have sidelobe levels of less then -20 dB. In simulation, these antennas exhibit low cross-polarization, but the axis of polarization slowly rotates as frequency is varied. The large difference in power received by orthogonal axes in the scale-model beam maps demonstrates polarization properties that are consistent with simulations that show $\pm 5^o$ polarization rotation and cross-polarization well

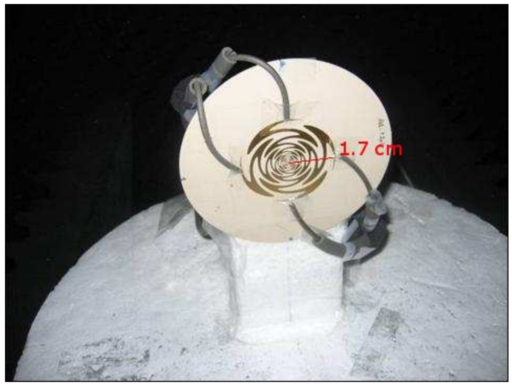


Figure 2. A 3-12GHz scale model center-fed with diodes for lens-coupled measurements was fabricated on 25 mil Roger's 3010 duroid. The antenna size is indicated in the photograph.

below the -20 dB level.

Polarization rotation has two effects on a CMB polarization measurement. The main effect is the average polarization rotation angle will be slightly different for each frequency band. This effect can be mitigated by doing a polarization calibration of the entire experiment for each frequency band. The second effect is depolarization, or signal loss, if there is significant polarization rotation within one frequency band. For our current design, a $\pm 5^o$ polarization rotation, the depolarization is at the 10^{-3} level for the worst case band placement at a frequency where the polarization rotation has a maximum slope with respect to frequency. This factor depends on the emission spectrum of the source, but the factor is sufficiently small that it should not cause any significant systematic error.

7. Superconducting prototype

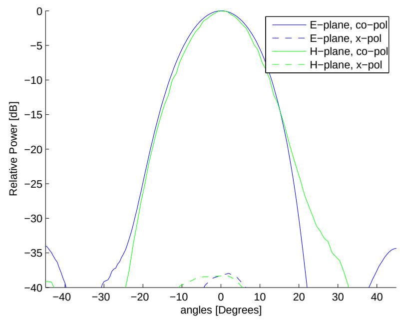
We have built and tested a superconducting millimeter-wave prototype pixel as shown in the photograph of Fig 4(a). This device was described in O'brient et al.[7]. A sinuous antenna with bandwidth from 90 to 270 GHz was connected to a simple diplexing RF filer where two bandpass filters are simply connected to the output of the antenna. The filters are optimized to work well as a diplexing pair using a the MMICAD microwave design program.

Frequency response for the two bands were measured and are shown in Fig. 4(b). The two measured bands are centered close to the design frequency. The efficiency of this pixel was low due to an avoidable design fault that gave a spurious coupling between the antenna feed lines and the antenna. Our subsequent designs have eliminated this unwanted coupling.

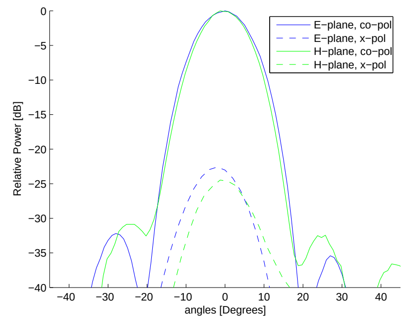
The diplexer design shown can be extended to a triplexer or quadplexer, but it is not appropriate for a larger number of bands. We have designed a built a scale model of a log-periodic RF channelizer that has eight frequency bands in an overall bandwidth of a decade as shown in Fig. 7[8, 9]. In this topology, the backbone and arms contain a series of low-pass and high-pass filters that are scaled in a log-periodic series. The placement, width, and isolation of the bands are adjustable parameters in the general design. The bands must be contiguous, but unwanted bands can be terminated in a passive resistor.

8. Antireflection coating

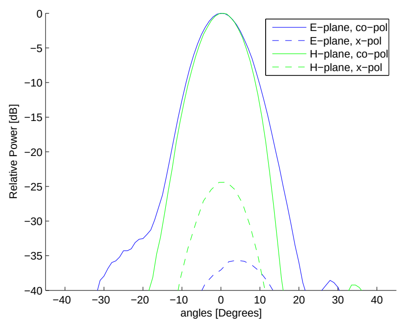
A key technology for the lens-coupled sinuous antenna is an broadband antireflection coating for the silicon lens. We have developed a four layer coating that uses three layers of a loaded resin (Rogers Corp. TMM) which is sold in several refractive indices and a final porous teflon (Zitex) layer. We have achieved 95% transmission over a 3:1 bandwidth ratio, and the performance of



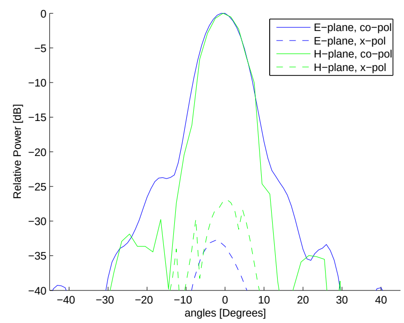
(a) 5 GHz Measured Cuts



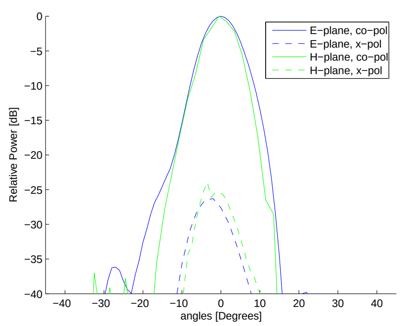
(b) 6 GHz Measured Cuts



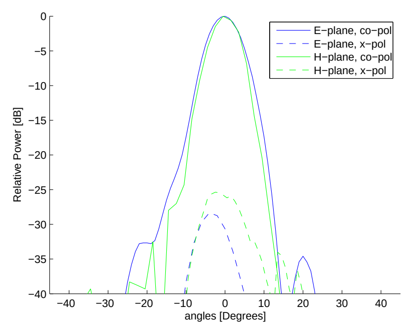
(c) 8 GHz Measured Cuts



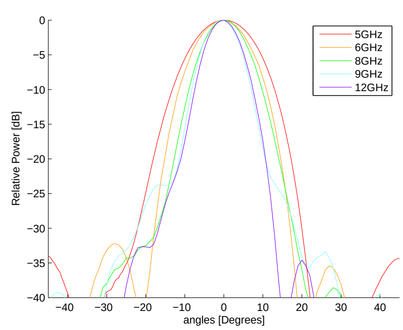
(d) 9 GHz Measured Cuts



(e) 11 GHz Measured Cuts

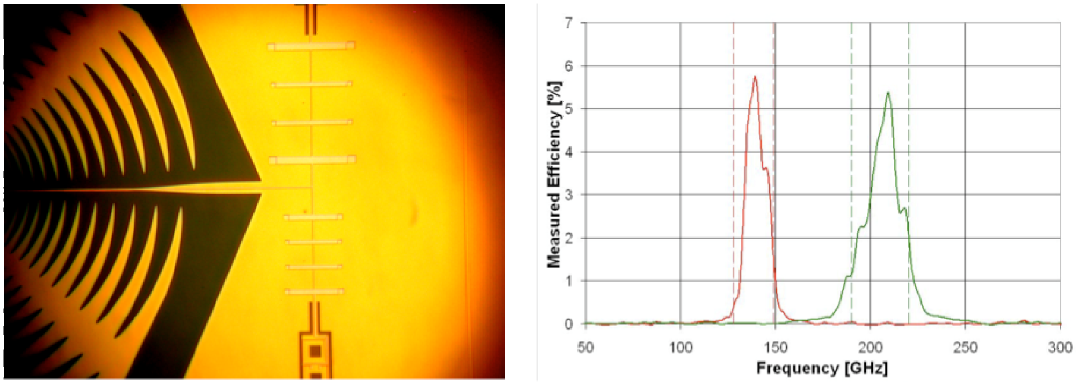


(f) 12 GHz Measured Cuts



(g) Several channels of E cuts

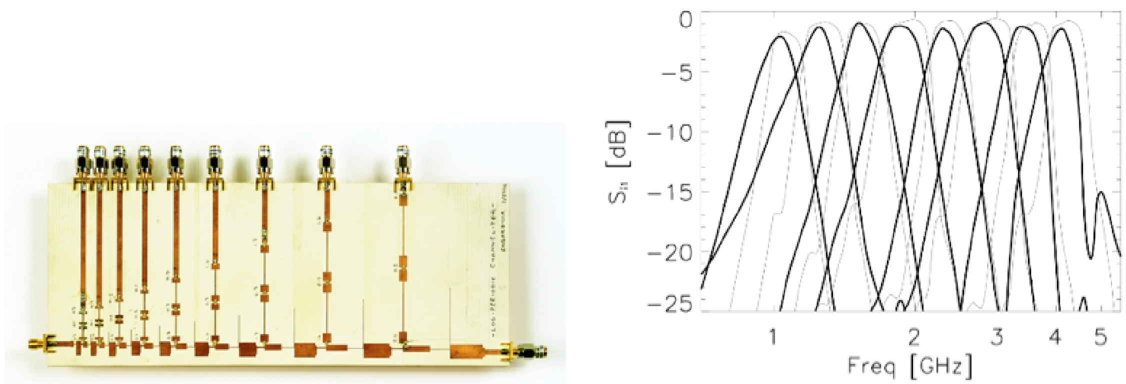
Figure 3. Measured Beams from the diode-fed lens-coupled sinuous antenna. First sidelobes are below -20 dB at all frequencies. No attempt was made to adjust the antenna with frequency to keep up with the polarization rotation, so these are not proper E and H cuts and some of the cross-polarized power is from misalignment. Despite this, the off-axis polarization seen in figs. (a) through (f) is very low. The magnitude of this cross-polarization is consistent with a wobble of $\pm 5^o$. The beams also narrow as frequency increases due to the contacting lens as seen in (g) where several co-polarized E-cuts are plotted together.



(a) Photograph of chip

(b) FTS Measured frequency response

Figure 4. (a) A photograph of a superconducting mm-wave sinuous antenna with RF diplexing filter that gives two frequency bands centered at 140 and 220 GHz. (b) End-to-end receiver measured passband response for the pixel shown in Fig 4(a) using an FTS. The efficiency of this pixel was low due to an avoidable design fault that gave a spurious coupling between the antenna feed lines and the antenna. Our subsequent designs have eliminated this unwanted coupling.



(a) Photograph of scale model

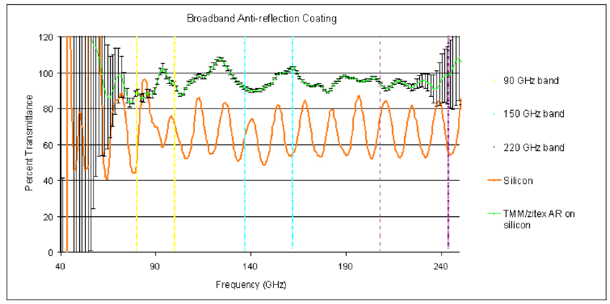
(b) Measured frequency response

Figure 5. (a) A photograph of a microwave scale model of an eight channel RF channelizer. The backbone and arms contain a series of low-pass and high-pass filters that are scaled in a log-periodic series. (b) Measured passband response for the model shown in panel (a). The dashed lines show the simulation of this circuit and the solid lines show measurements for this scale model. The apparent loss at the peaks of the passbands is largely due to power sharing between bands rather than dissipative loss.

this coating is the main limitation on the overall bandwidth of our designs.

Applications of this technology on curved surface are in development by thermosetting TMM on a curved form. At present, the TMM broadband coatings applied to curved surfaces are at TRL 2. In order to reach TRL 5, the following are necessary: Procedure for applying Zitex, or another low index layer, to a curved surface; Electromagnetic simulation of the effects of a layered AR coating on beam shape; Fabrication and optical testing of a prototype, including effects on beam shape; and technology scaling to efficiently produce many lenslets.

(a) Photograph of TMM coated hemisphere



(b) Measured transmission of silicon flat with two sided coating

Figure 6. (a) A photograph of a 5 mm diameter silicon hemisphere with single-layer TMM coating. This sample was cycled to immersed in liquid nitrogen with no damage to the coating. We have also fabricated multi-layer coatings that have been ground to the required thickness between coats. (b) Measured transmission for a flat piece of silicon with four layer coating. The flat has an antireflection coating on both sides, and therefore a lens with only a single coating would have an average of 95% transmission.

9. Future Work

This section describes the work needed to bring this technology to NASA TRL-5 such that it could be proposed for a CMBPOL mission. The minimum implementation of the lens-coupled sinuous antenna would use a "manifold" channelizer where up to four bandpass filters are simply connected to each of the two polarized output ports of the sinuous antenna as was done with our demontrated diplexer circuit. We need to improve upon the working prototype that we have already built and test it cryogenically for antenna patterns, polarization properties, band-definition, and optical efficiency. As mentioned, we have to test our broadband antireflection coating for the silicon lens in situ. Once these tests have been successfully achieved, the next step would be to demonstrate the design in a sub-orbital experiment e.g. POLARBEAR, EBEX, or SPT.

A more capable implementation of the lens-coupled sinuous antenna would exchange the simple manifold RF channelizer with a log-periodic RF channelizer. In this case, the number and placement of the frequency bands is more flexible and the entire bandwidth of the antenna can be used. Again, this step would have to be tested first in the lab using superconducting mm-wave pixels and then in a sub-orbital experiment.

Another future development would be to expand the overall bandwidth beyond our current design with a 3:1 ratio. Our design is currently limited by the antireflection coating on the lens, and therefore we would have to develop a coating with a larger overall bandwidth and develop a practical method for its manufacture.

Finally, another future development would be phase array the lensed antennas with the number of pixels in one phased array growing with reduced frequency. This development would relax the contrainst on the temperature of the cold aperture stop.

10. References

[1] Chattopadhyay, G. and Zmuidzinas, J., "A Dual-Polarized Slot Antenna for Millimeter Waves," *IEEE Transaction on Antennas and Propagation*, Vol. **47**, No. 5, 736 (1998).

[2] Myers, M. Ade, P.A.R., Engargiola, G. Holzapfel, W.L. Lee, A.T., O'Brient, R. Richards, P., Smith, A. Spieler, H., and Tran, H., "An antenna-coupled bolometer with an integrated microstrip bandpass filter," *Applied Physics Letters*, **86**, 114103 (2005).

[3] Rumsey, V. [*Frequency independent antennas*]. New York Academic Press (1966).

[4] Saini, K., Bradley, R., ”The Sinuous Antenna- A Dual Polarized Element for Wideband Phased Array Feed Application,” Electronic Division Internal Memo N0.301. National Radio Astronomy Observatory (1996).
[5] DuHamel, R. ”Dual polarized sinuous antennas,” US Patent No. 4658262 (1987).
[6] Griffin, M., Bock, J., Gear, W., ”Relative performance of filled and feedhorn-coupled focal-plane architectures” *Applied Optics* **41** 6543-6554 (2002).
[7] O’Brient, R., Ade, P., Arnold, K., Engargiola, G., Holzapfel, W., Lee, A.T., Myers, M., Meng, X., Quealy, E., Richards, P., Spieler, H., Tran, H., ”A Multi-Band Dual-Polarized Antenna-Coupled TES Bolometer,” *Journal of Low Temperature Physics* **151** Vol. 1 (2008).
[8] Engargiola, G., Holzapfel, W., Lee, A.T., Myers, M., O’Brient, R., Richards, P., Tran, H., Spieler, H., ”Planar Channelized Log-Periodic Antenna,” *IEEE 2005 International Symposium on Microwave, Antenna Propagation and EMC Technologies for Wireless Communications* **1** pp. 306-9 (2005).
[9] Engargiola, G., ”Channelized log-periodic antenna with matched coupling,” US Patent No. 7109821 (2006).