Optical Coupling

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Abstract. This paper describes contributions to the CMBpol Technology Study Workshop concerning optical coupling structures. These are structures in or near the focal plane which convert the free space wave to a superconducting microstrip on a Si wafer, or to the waveguide input to a HEMT receiver. In addition to an introduction and conclusions by the editor, this paper includes independent contributions by Bock on “Planar Antenna-Coupled Bolometers for CMB Polarimetry”, by Gunderson and Wollack on “Millimeter-Wave Platlet Feeds”, and by Lee on “Multi-band Dual-Polarization Lens-coupled Planar Antennas for Bolometric CMB polarimetry.”

1. Introduction
The Workshop has chosen the term Optical Coupling to mean structures in, or near to the focal plane which convert the free space wave from the optics to a superconducting microstrip on a Si wafer, or to the waveguide input to a HEMT receiver module. Other terms, such as feedhorn or antenna with orthomode transducer (OMT) are in widespread use for such structures, but they tend to be technology specific in a way that is not appropriate for this Workshop.
The mapping speed for a detector array in a given band depends on the throughput, $\Delta \Omega$ of the system and the detector sensitivity. It also depends on the Optical Coupling. A directly illuminated close packed detector array with pixel separation (dimension) $\lambda/2$ gives the fastest mapping speed. However, this scheme is little used for CMB measurements at millimeter wavelengths. It has several disadvantages including a large numbers of detectors and essentially no beam definition. Much of the throughput of each detector views the interior of the cryostat. This imposes stringent conditions on blackness, low temperature and temperature stability. It also lacks the RF shielding provided by some optical coupling schemes.

The optical coupling schemes described below all provide significant beam definition by expanding the diffraction aperture to several wavelengths. They can apodize the diffraction by tapering the illumination. They typically reduce both the number of detectors required and the mapping speed. For example, a close packed array with pixel separation (dimension) of $2\lambda$ requires an order of magnitude fewer detectors, but sacrifices a factor ~3 in mapping speed compared with the ideal directly illuminated array with the same throughput.

Most, but not all of the CMBpol mission concepts plan to use a cold aperture, or Lyot stop to supplement the beam definition provided by the optical coupling. This choice and the question of how aggressive the stop should be, depend on a number of system design choices and tradeoffs. In order to proceed with system design, it is necessary to understand the performance that can be achieved from the candidate technologies for optical coupling. Fortunately, much detailed information will be available since each of the optical coupling schemes discussed here has been used, or will soon be used in a major CMB polarization measurement.

In this paper, we present three quite different approaches to the challenge of optical coupling. The first contribution, by Gunderson and Wollack, describes the combination of ridged (scalar) horns. Ridged horns have a long heritage in space and the performance of ideal horns is well understood. These authors describe platelet fabrication technologies which can produce large arrays of such horns with near-ideal performance at acceptable cost. Most CMBpol mission concepts use focal planes with large arrays of superconducting bolometers at subkelvin temperatures. The use of ridged horns in such focal planes is likely to require a thermal break because arrays of horns may to be too heavy to cool to very low bolometer operating temperatures. Orthomode transducers (OMT), suitable for coupling ridged horns to bolometric detectors and HEMT amplifiers, are described in a separate paper by Wollack in these Proceedings.

The second contribution, by Bock uses a phased array of planar, subantennas for each pixel to synthesize a beam appropriate for coupling to the optics. In this aperture-synthesis approach, orthogonal arrays of polarization-sensitive subantennas feed microstrip outputs with orthogonal polarizations which couple naturally to microstrip filters and TES bolometers. All of these components are integrated on a single Si wafer. This approach has light weight and is very flexible. It can in principle produce coupling structures with any of several favorable properties. Interleaved antennas could even avoid the loss in mapping speed described above. In practice, however, there will be limits set by complexity that limit the number of these features that can be incorporated in a particular coupling structure. These issues, and the demands placed on fabrication by such high level integration, are being explored.

In the third contribution, by Lee, each pixel in a bolometric focal plane uses a broadband, planar, dual polarization, sinuous antenna, which is coupled to the optical beam by a hyperhemispherical Si lenselet. The microstrip outputs from the antenna can feed dual polarization diplexers, tripilexers, or multi band channelizers. The purpose of this approach is to
use focal plane area efficiently by detecting several frequency bands in each optical pixel. Two TES bolometers will be used for each frequency band. If this approach proves successful, it could have a major impact on the design of CMBpol. Some aspects of this impact are described. The level of development if this approach, however, is lower than either of the approaches described above. In particular, the techniques for broad band antireflection coatings for optical elements such as a waveplate or a lens must be demonstrated. An approach to coating the Si lenselets is described. Neither of the new approaches to optical coupling being developed by Bock and Lee have a heritage in space. Many space specific issues, such as sensitivity to ionizing radiation, are yet to be explored.
2 Millimeter-wave Corrugated Platelet Feeds

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Abstract. Feed horn arrays realized through platelet fabrication techniques represent a low cost, low risk approach to mass producing corrugated feed horns that maintain the superior performance of their electroformed equivalents. A brief review of the various approaches to fabricating these arrays is provided and their technical maturity is considered in comparison to their electroformed equivalents. The advantages and disadvantages of using corrugated platelet feed horns is provided, and an assessment of this approach’s technology readiness level is established for its use with both modular coherent receiver systems as well as planar, bolometric arrays.

2.1 Introduction

Millimeter and submillimeter wave imaging systems for radio astronomy and remote sensing require high efficiency coupling structures. The use of such antenna elements in the design of focal plane arrays enables reductions in observing time and improvements in calibration accuracy, while maintaining desirable imaging properties. The realization of such low-loss transitions from free-space to the sensor requires a conversion in the impedance level and electromagnetic symmetry while achieving the radiometer’s desired angular response, polarization, and frequency selectivity and maintaining an appropriate environment for optimal detector performance. The realization of such antenna elements in large focal plane arrays can potentially enable reductions in observing time and improvements in calibration accuracy while maintaining desirable imaging properties.

The conical corrugated horn is well known for its symmetrical Gaussian beam, low-side lobes, and cross polarization [1]. They have been the mainstay of optical coupling in cosmic microwave background (CMB) experiments. In particular, all of the experiments that have published detections of CMB polarization have used corrugated feed horns. These include DASI [2], CBI [3], CAPMAP [4], WMAP [5], Boomerang [6], and QUAD [7]. These experiments and their results provide ample evidence that a properly designed corrugated feed horn can meet the stringent systematic control associated with characterization of the CMB. Each of these experiments employed conventional techniques (either electroformed horns or directly machined horns) to fabricate individual feed horns that were then combined into arrays – none of which exceeded 50 elements. A difficulty with this approach arises when several hundred or a thousand elements is required as will likely be the case for a future CMBPol mission. In this case conventional machining techniques become impractical and/or very expensive.
Figure 1. The left hand figure shows the 91-element W-band array that has been developed for QUIET as it was undergoing return loss measurements. The dimensions of the 20 kg array are 42.8 cm point to point, 37.0 cm across the flats, and 12.9 cm thick. The right hand figure shows that the platelet array consists of 5 thick plates each with 18 corrugations per horn hole, 13 platelets each consisting of a tooth and a groove, and a baseplate. The right hand figure also shows how the access holes open to light weighted pockets through the bulk of the structure.

2.2 Technical Description

A low cost alternative makes use of mass production to generate a pattern of holes on a large number of thin platelets that are subsequently bonded together to form a platelet array of corrugated feed horns. At centimeter to millimeter wavelengths this can be realized by direct machining bulk or sheets of material. In the submillimeter, chemical milling of the raw material is compatible with achieving the desired tolerances.

2.2.1 Design Features

The need for large numbers of corrugated feed horns was foreseen by [8] who were the first to develop platelet arrays of corrugated feed horns for remote sensing applications. These arrays consisted of ~100 thin sheets of zirconium copper with identical patterns of slightly different diameter holes etched into the plates. When these were diffusion bonded together, they formed a platelet array of corrugated feed horns. Recent variants on this approach have used different fabrication techniques (see below), but the overall design features have not changed drastically. In particular, the platelet array provides a flexible approach incorporating pocketing that can be used for either fluid cooling (important for [8]), light weighting, or to resolve complex interface issues as described in [9]. In addition, profiled corrugated feed horns such as those deployed in DASI can easily be implemented.

The largest departure from the fabrication described in [8] has been implemented in [9] who use a combination of thin platelets (each with a machined tooth and groove at the position of each horn hole) and series of thick plates each with 9-to-18 machined corrugations at the position of each horn hole. This design resulted in a significant reduction in setup time during machining, it minimized machining errors associated with the setup process, it significantly reduced the part count, and it eased the precision alignment and assembly process. Many of the design features that have been incorporated into platelet array assemblies are illustrated in Figure 1.

2.2.2 Fabrication Techniques

There are a number of techniques that have been employed to fabricate platelet arrays. These techniques use different materials, different material removal methods and different bonding techniques. These are summarized in Table 1. The material removal and to a lesser extent the choice of materials breaks depends on the frequency range. At low frequencies, computer
numerical control (CNC) machining provides enough accuracy to define the holes. For fixed antenna gain, the horns are larger at lower frequencies and this drives the design toward lower density materials such as aluminum. At higher frequencies, etching is necessary to precisely remove the material, and lower loss materials, such as copper, are preferred.

Coupling platelet feed horns to arrays of coherent receivers is straightforward since they can all reside at the same temperature, and the devices that follow the feeds, such as orthomode transducers (OMT) and septum polarizers, are waveguide based. Coupling platelet feed horns to an array of bolometric detectors is more challenging – see section 2.3. One of the challenges is to deal with the differential contraction between the metallic platelet array and the silicon used in bolometric arrays. One solution that is being pursued at the National Institute of Standards-Boulder [14], is to micromachined silicon platelets using Deep Reactive Ion Etch (DRIE) to enable easier coupling to arrays of bolometric detectors. Once the array structure is metalized, aligned, and fused, a low thermal mass structure with desired thermal and mass properties is envisioned. The resulting structure would also be thermally matched to silicon detector wafers, thus simplifying the alignment of the feeds to the detectors.

2.2.3 Coupling and Integration

For CMB polarization experiments, corrugated feeds are sometimes used with a waveguide polarization diplexer such as an OMT or a septum polarizer. For coherent receiver systems, these can be realized in waveguide assemblies and bolted onto the back of the platelet array. A more detailed description of these devices and how they would be used in both coherent and bolometric systems is provided in these proceedings [15]. For a bolometric array using a metallic platelet array, a thermal break would likely be necessary between the platelet array operating at 2-4 K and the bolometer array at 0.1-0.3 K. Introducing such a thermal break is challenging because it can cause unnecessary signal losses and it places cryogenic alignment between the horns and the detectors’ waveguide inputs. One promising approach uses a photonic waveguide joint [16]. A dual-mode realization of this structure allows control over the power transport in the waveguide interface, a significant reduction in the necessary alignment tolerance, and a natural location for the detector and its supporting circuitry. This sensor configuration provides an environment which is compatible with the spaceborne thermal and ionizing radiation environments.

The final coupling occurs between dual mode waveguide (i.e. either rectangular or circular waveguide) and a planar structure – either a coherent receiver module or a bolometric detector element. Many approaches have been used to realize the transition between the waveguide and

| Reference | Material | Material Removal | Bonding            | # of Elements | Frequency (GHz) |
|-----------|----------|------------------|--------------------|---------------|-----------------|
| [8][10]   | ZrCu + Al5052 Cu-plated SS#347 | Etching           | Diffusion Bonding  | 9, 16         | 90              |
|           |          |                  |                    | 16            | 626             |
| [9]       | Al6061   | CNC              | Diffusion Bonding  | 19            | 40              |
|           |          |                  |                    | 91            | 90              |
| [11][12]  | Copper   | Etching          | Diffusion Welding  | 1020          | 500             |
|           |          |                  | + Epoxy versions   |               |                 |
| [13]      | Brass    | CNC              | No bonding         | 31            | 100             |
| [14]      | Metalized Silicon | DRIE | TBD                 | TBD            | 150             |
the detector. In the coherent case there are mature techniques to achieve this coupling and representative examples are provided in following references [17]. In the bolometric case, several coupling approaches have been explored and implemented [18]. Efforts to realize this coupling function via a planar OMT are arguably at a lower level of technical maturity; however, they are being investigated by several groups [15].

![Diagram showing return loss measurements](image)

**Figure 2.** Return loss measurements from one of the horns in the QUIET 91-element W-band array is compared to an electroformed equivalent of the horn.

### 2.3 Technical Maturity

#### 2.3.1 Performance Metrics

One measure of the technical maturity of platelet arrays is to compare their performance against theoretical models and/or electroformed versions of the platelet array feed horns. Most of the papers above that describe platelet feed horn array fabrication also summarize their observed performance characteristics. The quantities typically measured and reported include return loss, co- and cross-polar beam patterns and insertion loss.

**Return Loss**

Return loss is measured by connecting one port of a vector network analyzer to a horn with a circular to rectangular waveguide transition and then recording the S11 parameter while the horn is terminated by a piece of microwave absorber. Given this measurement approach the transition between the waveguide and the feed throat dominates the result. Return loss measurements are particularly sensitive to machining errors (e.g., [5]) and imperfect bonding or flanging which can be manifested as resonances (i.e., ‘suck outs’) in the return loss spectrum. Return loss values of 30 dB can be designed into corrugated feed horns over >25% bandwidths and realized in electroformed versions. Return loss measurements of platelet feed systems are typically close to but not identical to their electroformed counterparts. As an example, Figure 2 shows return loss values closer to 25 dB were observed in the lower third of the QUIET detector module’s band (88-93 GHz), while from 93-103 GHz, the return loss was greater than 30 dB (see Figure 2). Even the 25 dB return loss is an acceptable level given that the septum polarizer used for QUIET’s polarization diplexing is expected to dominate the return loss. Perhaps just as important, and not something that has been consistently reported in previous publications is that the return loss was
very repeatable (typically +/- 1 dB for return losses <30 dB) from horn to horn for both the 19-element Q-band array and the 91 element W-band array.

**Beam Patterns.**

Beam pattern measurements are another diagnostic used to evaluate the performance of platelet arrays. All papers that have reported on platelet arrays have also reported some subset of E- and H- plane, co- and cross-polar beam measurements and compared them to either theoretical predictions and/or electroformed equivalents. The results are generally encouraging, although, as with the return loss measurements, there are cases where there are some noticeable deviations between the measured platelet response and the theoretical prediction or the electroformed equivalent. The pathologies associated with the platelet arrays that would give rise to these deviations have not been fully investigated, though in most cases the deviations are small enough so as not to cause significant deleterious effects.

The theoretical predictions of corrugated feed horn’s beam patterns and return loss are extremely mature. One example is the software CCORHRN from YRS Associates which was used to design both the WMAP and QUIET feeds and has been experimentally verified down to the -80 dB level [5]. This agreement is possible due to the high degree of axial symmetry present in the structure studied. Finite element codes have been used to study the influence of a systematic reduction in axial symmetry and have found that the desired response is tolerant to adiabatic errors in the layup of the structure at level relevant to this application. Thus, in principle these pathologies could be investigated at a greater detail if necessitated by other design considerations. A measurement of particular relevance to CMB polarization experiments is the cross-polar response of the feed horns, and this is typically under reported in the above references. For an axially symmetric feed structure the cross-pol is a measure of asymmetry between the E- and H-plane angular responses. In the limit other modes are present; this simple interpretation can break down thus requiring knowledge or measurement.

Measured examples of beam pattern measurements from one of the horns on the QUIET 19-element Q-band array are shown in Figure 3. These illustrate that the co-polar beams match the theoretical predictions as well as the electroformed measurements very well down to the 30 dB

![Figure 3. Co-polar and Cross-polar beam patterns in both E and H planes for one horn in the QUIET 19-element Q-band array are compared to measurements of an electroformed equivalent horn as well as to theoretical predictions. Theoretical predictions of the cross-polar levels as well as the electroformed horn’s measured E plane were <40 dB and are not shown.](image)
level. The peak cross polar levels are predicted to be $<-40\, \text{dB}$, while typical peak measured levels are in the -30 to -40 dB regime. These measured levels are higher than the theoretical predictions and are believed to be due to misalignments in the test apparatus. Measurements are currently being performed to confirm this.

**Insertion loss**

Insertion loss measurements are often difficult to perform because, for well manufactured horns with high electrical conductivity, the insertion loss would only manifest itself as a reduction in transmission efficiency (i.e., increase in system temperature). For applications at hand the influence of the insertion loss is expected to be subdominant compared to other potential sources of in-band emission. In cases where there is incomplete diffusion bonding, or as in the case of [13] where there is no bonding at all, increased insertion loss at cryogenic temperatures might be experienced due to the presence of gaps if insufficient platelet layer compression is realized. Crude measurements were performed at room temperature on the QUIET arrays by shorting the horn apertures with a metal plate during the room temperature return loss measurements, and typical values of $<0.1\, \text{dB}$ were observed. Further reductions would be anticipated upon cooling the feed array structure. Characterization of copper platelet waveguide sections at room and cryogenic temperatures indicate that loss within a factor of two of theoretical is achievable at millimeter wavelengths [11].

2.3.2 Readiness

In addition to the performance milestones discussed above, it is useful to establish the platelet array’s stage of technology development. Up until very recently, all platelet arrays mentioned above were prototypes that were tested in the lab to various levels. Just recently (7/08) the first platelet array has moved out of the lab and into the field to begin taking data as part of the QUIET 19-element Q-band array. This has just been deployed to the Chajnantor Observatory on the Atacama plateau in Chile, and the 91-element W-band array will follow in early 2009.

2.4 Benefits and Disadvantages of Platelet Arrays

2.4.1 Benefits

1) Platelet arrays of corrugated feeds use a well established machining/fabrication processes for metallic structures which are compatible with reliable cryogenic end use.

2) Platelet arrays of corrugated feeds represent a viable technological path toward large number of detector elements in a focal plane.

3) Platelet arrays of corrugated feeds provide a well controlled and repeatable illumination pattern that enables desired return loss, beam shape, spill, and instrument polarization response.

4) Platelet arrays of corrugated feeds are compatible with high performance polarization diplexing and microstrip based filtering approaches and in addition they allow natural separation of IR and millimeter wave filtering needs.

5) The theoretical predictions of platelet array performance are very mature.

2.4.2 Disadvantages

1) Relatively high metal mass/volume used in convention approach required lightening to produce more optimal component for space borne application.

2) The simplest platelet array realization requires a flat focal surface. As in all antenna illumination approaches, the $f'$ and number of optimally performing detectors pixels are coupled in specification of the design. The necessary system sensitivity may push one toward a configuration with multiple optical assemblies in order to achieve the required number of pixels on the sky with the desired angular resolution.
3) The detector coupling structures are waveguide based. As a result, the packaging requirement can be more demanding than planar array based approaches
4) Depending upon system implementation, quasi-optical IR blocking filters may be required after feed illumination definition in order to achieve the desired thermal environment for the detector.

2.5 Technology Readiness Level (TRL)

The technical readiness of platelet feed array structures when used in conjunction with cryogenic coherent receiver systems is at level five or higher. For bolometric imaging systems the interface between the platelet array and the detector forces one to assign a lower level of readiness for the technology. Laboratory efforts in this area are underway and a TRL of ~3-to-4 is estimated for the approach at the present time. The resources required to push this technology to TRL five for this case will be dominated by detector and system level costs associated with fielding instruments which utilize and validate this technology.

Acknowledgements
The development of the QUIET 19 element Q-band array and the 91 element W-band array were supported by JPL and the NSF. William Imbrie, David Leibovitch, Joelle CooperRider, Raul Monsalve and Yuniorn Savon were integral in the design and testing of the arrays. Todd Gaier, Suzanne Staggs and Glen Nixon provided assistance with return loss measurements.

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3. Planar Antenna-Coupled Bolometers for CMB Polarimetry

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Version 5, 19 August 2008

Abstract. Antenna-coupled detectors provide all the functions required of a CMB polarimeter, including beam formation, spectral band definition, and polarization analysis. Planar antennas are fully lithographed devices that do not require coupling optics, and thus readily scale to the production of large focal plane arrays. Antennas coupled to direct detectors such as transition-edge bolometers can realize background-limited sensitivity, and, in a single technology, cover the range of frequencies likely to be required by a future post-Planck satellite experiment for foreground monitoring and removal. We have successfully tested single devices at 150 GHz with the desired beam shapes, pass bands, and polarization properties with high optical efficiency, and are now developing focal plane arrays for the BICEP2 and SPIDER experiments.

3.1 Introduction

Antenna-coupled detectors provide polarization discrimination, beam formation and spectral band definition, and are thus a natural approach for CMB polarimetry. A planar antenna consists of a distributed arrangement of sub-antennas coherently summed with a combiner network. The response of the sub-antennas in coherent combination gives higher forward beam directivity than that of a single sub-antenna in isolation. The shape of the main beam is controlled through the size of the antenna, and the field amplitude and phase in each sub-antenna. This technique of beam formation eliminates the need for additional coupling optics, such as lenses or feedhorns. Planar antennas are a very flexible technology that can be used to produce highly tapered, directed, and/or overlapping beams with multiple frequency bands and the simultaneous analysis of multiple polarization parameters.

A network of sub-antennas with a combining network is shown in Fig. 4. The sub-antennas must have a minimum spacing to avoid generating grating lobes or surface waves, approximately given by the Nyquist condition for sampling a surface wave, \( s < \lambda_{\text{min}}/2n \), where \( s \) is the spacing, \( \lambda_{\text{min}} \) is the shortest wavelength in the passband and \( n \) is the index of the substrate. A more exact analysis indicates the spacing can be somewhat relaxed to \( \sim \lambda_{\text{min}}/1.2n \). The size of the antenna, effectively the number of sub-antennas combined, is determined by the desired beam width, \( \Delta\theta \approx \lambda/d \).

3.2 Advantages of Planar Antennas

Unlike ‘cavity-coupled’ bolometers, such as the devices used on Planck, where the absorber is approximately a wavelength in diameter, antenna-coupled bolometers use a resistive transmission line termination to absorb RF power, and this termination can be as small as lithographic techniques permit. Antenna-coupled detectors can operate over the range of frequencies anticipated for CMBPOL, 30 – 300 GHz [19], by scaling the
antenna and filter design but leaving the detective element unchanged. This approach overcomes the limitation of bolometers with cavity-coupled absorbers, which have not been designed to operate at frequencies lower than 70 GHz. While it is possible this technology could be pushed to still lower frequencies, the lowest frequency Planck devices began to show both lower mechanical yield and slower time constants due to their large physical size.

Fig. 4. Schematic of a planar antenna (a). The sub-antennas are slots (red and blue lines) combined by a microstrip summing network (grey lines). There are two antennas in this configuration which are closely interleaved, one in vertical polarization and one in horizontal polarization, and the slots and summing networks are independent. Actual antennas combine larger numbers of sub-antennas (see Fig. 5c) than shown in this illustration. The antenna is illuminated through the silicon substrate (b), with microstrip taps coupling to the slot antennas. A $\lambda/4$ layer of fused quartz serves as an anti-reflection coating. A reflective $\lambda/4$ backshort is used to improve the optical efficiency, preventing radiative loss to free space.
Planar antennas are entirely lithographed and thus naturally lend themselves to the production of large focal plane arrays. Planar antennas do not require coupling optics such as lenses or feedhorns, but do require a flat anti-reflection coating. This coating can be quite simple, e.g. for devices with 30% bandwidth a single √\n coating suffices, and, for devices made on Si, a tuned wafer of fused quartz is a highly efficient coating. Compared with lens-coupled antennas [20][21], planar antennas eliminate the alignment between the lenses with the exciting antenna, and the potentially difficult problem of anti-reflection coating the highly curved lens surface. Compared with feedhorn-coupled antennas [22], planar antennas eliminate the mass of the feedhorns. The mass of such structures at sub-K temperatures drives the design of the mechanical suspension and the sub-K cooling system, and can have adverse systems implications.

Planar antennas provide an elegant means for controlling the beam pattern [23]. With a suitable summing network, the amplitude and phase of the electric field can be chosen at every sub-antenna. For example, by changing the phase across the sub-antennas, the beam direction can be controlled. In particular the beam can be steered away from normal incidence, while keeping the focal plane flat, so that planar antennas can be used with non-telecentric optics. By varying the amplitude of the electric field over the sub-antennas, the beam pattern can be tapered to reduce spillover off the telescope optics. As the electric field can be controlled exactly at every sub-antenna, the illumination pattern from a planar antenna can be highly optimized. This degree of control is not possible with lens coupled antennas. Planar antennas can be designed to eliminate differential beam ellipticity, because the x-y beam widths are determined by the x-y field distribution of the sub-antennas, and only weakly by the radiation pattern of the sub-antennas themselves.

A future CMB polarization mission will require efficient use of the available field of view provided by the optics. Planar antennas offer several advantages for increased packing density. Like lens-coupled antennas, planar antennas can be operated in multiple polarizations simultaneously, or in multiple bands. The antennas are currently designed to extract a single Stokes polarization parameter (Q or U) by differencing 2 matched detectors and antennas, providing common-mode rejection of temperature anisotropy, unpolarized emission from the optics, and focal plane temperature fluctuations. Multi-color designs are also possible, although this brings the additional difficulty of anti-reflection coating over a wide bandwidth and controlling the beams in multiple bands. We have demonstrated a design that realizes more than an octave of bandwidth in one polarization [24].

In any focal plane, configured with either antennas or feeds, there is a tradeoff between the density of detectors and the illumination pattern on the primary aperture. We have compared the mapping speed of various focal plane architectures assuming the available AΩ product of the available focal plane is held constant [25]. A design with higher edge taper on the primary necessitates a larger antenna (or feed). Focal planes with low spillover, characteristic of CMB instruments, suffer an overall loss in mapping speed compared to bare detector focal plane arrays, which detect all the incident photons but provide no beam control. An aggressive design with ~10% edge spillover, typical of 2fλ antennas or feeds, suffers an overall loss in speed of a factor of ~3 compared with an ideal bare-detector focal plane array. More conservative designs with lower spillover have even larger losses in speed due to the fact that the pixels must be larger. This factor
can be recovered using a focal plane array of planar antennas with overlapping field
distributions [26]. While the design of such a focal plane array will be involved, it is
possible to simultaneously control the illumination on the primary aperture, while fully
realizing the ideal mapping speed [27].

3.3 State of Development

We have developed focal plane arrays of planar-antenna detectors [28] as shown in
Fig. 5. The device has two interleaved antennas detecting vertical and horizontal
polarization, terminated in two TES bolometers. The sum and difference of the two
signals produces Stokes Q and I. The sub-antennas are slot antennas in a
superconducting Nb ground plane, and the antenna is backside illuminated through the
substrate Si. A single λ/4n layer of fused quartz is placed on the backside Si for anti-
reflection coating. The slot arrangement places the RF components of the detector
(summing network and stripline filters) behind the ground plane so they cannot couple to
incident radiation.

The slots are interleaved, as shown in Fig. 4, to achieve the required sub-antenna
spacing. Each slot is fed off center with two microstrip taps, at a location where the
antenna has a suitable impedance to conveniently match to microstrip. Each tap is
combined with a rectangular capacitor to tune out the reactance of the antenna. The sub-
antennas are combined by a summing network, which in the time reversed sense couples
equal amplitude and phase to each sub-antenna. This arrangement gives a beam pattern
resembling a two-dimensional sinc function.
Fig. 5. (a) Focal plane array of planar antenna-coupled bolometers produced on a 100 mm wafer consisting of 64 antennas each with two TES bolometers measuring vertical and horizontal polarization. (b) A focal plane utilizing 4 such arrays with a total of 512 TES bolometers. The focal plane arrays are read out with time-domain SQUID multiplexers, mounted at the top and bottom of the circuit board. Each planar antenna (c) is a dual polarization device with the sub-slot driven with identical phase and amplitude by a combining network. The antenna is designed to produce equivalent beam widths along the co-polar and cross-polar direction, eliminating the false polarization signal caused by differential ellipticity, and identical beam centers in the two polarizations, eliminating the false polarization signal caused by differential pointing [29][30]. The summing network combines the RF signal onto a single transmission line which then passes through a lumped-element RF filter (d) and then to a thermally-isolated termination resistor (e) where the thermal rise from dissipated RF power is detected by a TES bolometer.

These antennas were designed to be coupled to f/2 optics with a cold absorbing aperture stop. The antennas are 8 mm on a side and operate at 150 GHz, giving 2λ pixels at f/2. We chose to have an aggressive spillover in order to use smaller pixels with a higher packing density. The aperture is approximately near the first beam minimum, and the secondary lobes fall onto the aperture stop giving a power spillover of
~10%. Tapering the beam produces little improvement for an antenna of this size. Larger antennas with tapering would provide better beam control, but at the price of reduced packing density.

**Fig. 6.** (Left) Measured spectral response of an unfiltered (orange) and filtered (blue) antenna, including the quartz anti-reflection coating, antenna, combiner network, and meander absorber but not including the \(\lambda/4\) backshort. The response curves are absolutely normalized by measuring the response to a cryogenic blackbody source (Right) so that the measured response convolved with the blackbody function with single-mode coupling in one polarization produces matches the measured power from the blackbody source. This efficiency includes the filter, absorber, antenna, anti-reflection coating, and (absorbing) backshort.

**Fig. 7.** Beam patterns of a filtered dual-polarization antenna in vertical and horizontal polarizations measured with a chopped thermal source. The original of the small deviations seen in the above panels are not clear, though we have seen evidence that reflections in the testbed windows and filters can effects at this level.

Measurements of full planar antenna-coupled TES bolometers are shown in Figs. 6 and 7. The response was measured looking out through a low-pass filter stack and window into a Fourier-transform spectrometer. The spectral bandwidth of the antenna is \(\Delta\nu/\nu = 35\%\). The efficiency shown in Fig. 6 was normalized by measuring the response to a cryogenic blackbody source. The devices show high optical efficiency, typically 50 – 80%, measured using an absorbing backshort. This efficiency is notably improved
over that of corrugated feeds combined with cavity-coupled polarization sensitive bolometers [31][32], typically 20 – 40 %. Using a λ/4 reflecting backshort will recover the ~10 % loss that the antennas radiate into the vacuum side of the device [33]. The beam patterns, measured with a chopped thermal source and shown in Fig. 7, are highly symmetric and well matched. The devices clearly show the expected characteristic two-dimensional sinc pattern and secondary sidelobes. The cross-polarized response, measured with a chopped source and a rotating polarizing grid, is < 3 %.

Breaks or shorts in the feed network can cause imperfections in the beam patterns. The effect of a single missing sub-slot in the feed network shown in Fig. 5c is fairly subtle, causing a deviation from the expected pattern at the -28 dB level, which is not measurable with our existing test apparatus. Of course more missing slots cause larger deviations, and the deviations depend on the location of a defect in the feed network. We carried out electrical continuity measurements of long Nb/SiO2/Nb test striplines with tapered sidewalls that indicate defects in freshly deposited and bias-sputtered dielectric are basically negligible. However, in fully processed wafers, we have noticed occasional shorts between the wiring layer and the ground plane, apparently due to pinholes in the dielectric layer developing as a result of the additional processing steps required to form the TES and absorber. We are currently testing several techniques to reduce defects to a negligible level for arrays.

3.4 Future Developments

With single-element 150 GHz planar antennas successfully demonstrated, we are now in the processes developing focal plane arrays. Testing of these focal plane arrays will be used for process control at wafer level and wafer to wafer that can affect the optical performance, e.g. fabrication errors (shorts and breaks) in the combining network and variability (thickness, width and index) in the microstrip dielectric. The next step is to expand the frequency range of operation. We are currently testing designs for 100 GHz, and ultimately plan to demonstrate devices in bands ranging from 30 – 300 GHz.

A simple modification to the antennas allows each pixel to sense Stokes Q and U simultaneously. This may provide improved systematic error control, since otherwise Stokes Q and U must be extracted either by using different detector pairs, or using the same detector after a boresight rotation and corresponding time interval. To measure Q and U, two antenna output lines E_x and E_y may be first power divided and half of each line routed to two detectors producing E_x^2/2 and E_y^2/2. The remaining half can be routed though a broadband 180° hybrid followed by two detectors, producing (E_x+E_y)^2/4 and (E_x-E_y)^2/4. The difference between each detector pair produces Q and U respectively. If the detectors are photon noise limited, there is no sensitivity penalty in such an arrangement. Two balanced hybrids can be used in place of one hybrid to minimize differential spectral features from the hybrid.

Tailoring the field amplitude and phase distribution over the antenna can provide improved sidelobe control, an important development for optical systems without a cold stop, e.g. the Planck telescope or crossed-Dragone optics. Because the field distribution over the antenna may be designed exactly, planar antennas are an ideal technology for such precise beam control. With a focal plane array of antennas, the field distribution may be shared between multiple detectors to produce overlapped beams to simultaneously provide beam formation with maximum mapping speed, though this will require the development of complex and dense feed networks with crossovers.
Planar antennas are a flexible technology. Some attributes represent enabling technology for CMB polarimetry from space, while other capabilities are merely advantageous. We have listed a set of milestones to demonstrate readiness (TRL ~ 6) for space, and list separately capabilities that provide additional advantageous that would benefit CMBPOL. The milestones described below are what we consider to be the necessary and minimum demonstration of technical readiness. Where the capability is likely to interact with a full system, we recommend a demonstration at instrument level. Where the required performance can be fully characterized in the laboratory we recommend the development of a single pixel, and assume that space-qualified focal plane arrays developed under the auspices of the future CMBPOL mission can be based on this demonstration. Full focal planes (see Fig. 5b) intended for the BICEP2 and SPIDER experiments are currently in development to fulfil milestone #2. These would provide an end-to-end test in a representative instrument, demonstrating suitability for a space-borne densely-packed focal plane appropriate for an optical system with a cold aperture stop.

| Capability | Advantage for CMBPOL | Technical Challenges | Milestone |
|------------|----------------------|----------------------|-----------|
| Optical coupling | Beam formation, polarization analysis, band definition | Antenna and filter design, RF properties and losses | Pixel demonstration (completed at 100 and 150 GHz) |
| Focal plane arrays | System sensitivity | Process uniformity and reliability | Field focal plane arrays in a CMB receiver |
| Frequency coverage | Foreground removal | Antenna and filter design | Pixel demonstrations from 30 to 300 GHz |

| Attributes Necessary for Some CMBPOL Mission Designs |
|------------------------------------------------------|
| Highly tapered beams | Sidelobe control for optics without a cold stop | Antenna and combining network design | Pixel demonstration in a single band |
| Simultaneous Stokes I, Q and U | Systematics control, depends on scan strategy | Hybrid design and spectral band matching | Pixel demonstration in a single band |

| Attributes Advantageous for CMBPOL |
|-----------------------------------|
| Directed beams | Use of non-telecentric optical designs | Antenna and combining network design | Pixel demonstration in a single band |
| Multiple frequency bands per antenna | System sensitivity | Diplexer design | Pixel demonstration in multiple bands |
| Overlapping antennas | System sensitivity | Antenna and combining network design, transmission line density and crossovers | Focal plane array demonstration in a single band |
| Polarization modulation | Noise stability | Active device to switch polarization states, RF design | Field focal plane arrays in CMB receiver |

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

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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. Finally, a sketch of a mission design using a single 30-centimeter-diameter aperture and two sizes of multichroic pixel is presented.

4.1 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 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.
4.2 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 \( \lambda \). 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 \( \theta_{\text{beam}} \sim \lambda / \text{length} \sim 1 \text{ radian} \). 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 [34].

Before working on the multichroic antenna, we developed an antenna-coupled bolometer using the well characterized double-slot dipole design [34]. We integrated the antenna with band-defining planar filters and Transition-Edge Sensor (TES) bolometers [35]. We have been able to demonstrate ~ 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.

4.3 Log-Periodic Antennas

Planar dipole antennas have less than 40% fractional bandwidth over which the impedance match offers better than -10dB return loss [34]. 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 \( \tau \), 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 [36]. The bandwidth of these antennas is only limited by the size of the smallest and largest log-periodic cells.

4.4 Lens-Coupled Sinuous Antenna

The sinuous antenna (Figure 8) is a log-periodic antenna that has been known for useful polarization properties since DuHamel invented it in the 1980s [37]. The edges of the switch-backing arms follow the equation [38]:

\[
\varphi = \alpha \sin \left( \pi \ln\left(\frac{r}{R_0}\right)/\ln \tau \right) \pm \delta \quad \text{for } R_0 < r < R_0 \tau^N 
\]  

Each of the four arms snake through an angle of \( \pm \alpha \) every rescaling of \( \tau \). Typical values of \( \alpha \) are between 30° and 70°, while typical values of \( \tau \) 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 8. 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 ±4.5° as a slowly varying function of frequency.

4.5 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 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 [39], 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.

4.6 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 $\varepsilon = 12$ 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. 10. 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 $\pm 5^\circ$ polarization rotation and cross-polarization well 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 $\pm 5^\circ$ 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.

### 4.7 Superconducting Prototype

We have built and tested a superconducting millimeter-wave prototype pixel as shown in the photograph of Fig 11(a). This device was described in O'brient et al. [40]. 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 the MMICAD microwave design program.

Frequency response for the two bands was measured and is shown in Fig. 11(b). The two measured bands are centered close to the design frequency. The efficiency of this
Figure 10. 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 rotation of ±5°. 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.
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. 14 [41,42]. 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.

4.8 Antireflection Coating
A key technology for the lens-coupled sinuous antenna is a 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 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.

4.9 Low-mass Mission Concept
In this section, a sketch of a mission design using multichroic pixels is presented. For one type of telescope design, focal plane area and telescope throughput scales linearly with aperture area. Even when different telescope designs are included, there is a general trend of increasing throughput with telescope size. Therefore, if a minimum throughput is required for sensitivity, it will drive a CMB polarization mission design toward one large aperture or multiple smaller apertures. The JPL-EPIC designs reflect this tradeoff. EPIC-LC has six 30-centimeter diameter apertures and EPIC-comprehensive has one 2.5-meter aperture.

The mission design presented here uses a single 30-centimeter-diameter aperture cooled to 2K (see figure 14(a)). Two types of pixel are used. A low-frequency pixel with bands centered at 30, 40, 50, 65, and 85 GHz and a high-frequency pixel with bands centered at 110, 145, 190, 242, and 314 GHz (see figure 15). Since each pixel covers a factor three in total bandwidth range, the spillover efficiency and aperture efficiency will vary with frequency for a single pixel. The pixel diameter is chosen with a compromise between edge taper on the Lyot stop (which determines the sidelobe level) at the lowest frequencies and mapping speed at the highest frequencies. For the design presented here, the overall middle of the frequency range was emphasized such that edge taper at the 30
Figure 11. (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 11(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.

Figure 12 (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.

GHz end and the mapping speed at the 314 GHz end are compromised. The overall sensitivity is comparable to the JPL-EPIC concepts.

4.10 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 demonstrated 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.

Fig 13 (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.

Fig 14 (a) ZEMAX geometric optics simulation of a 30-centimeter-diameter aperture crossed Dragone telescope. An aperture stop is included at the entrance of the telescope. The focal plane is limited to 26 centimeters in height along the symmetry axis of the telescope due to vignetting. The entire telescope would be cooled to 2K. This design was produced by Huan Tran. (b) Calculated Strehl ratios for 850, 450, and 150 GHz, with 150 GHz line having the highest Strehl ratio in the figure. The assumed focal plane uses the central half of the focal plane area for 110-314 GHz and the outer half of the area for 30-85 GHz. This allocation emphasizes the 110-314 GHz range.
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, a mature design would need to take system level issues into account such as the characteristics of the front-end optical filtering chain, array temperature control and stability, and robustness against ionizing radiation, surface charging, and radio-frequency interference.

Acknowledgements
This paper summarizes work that has been previously reported largely by O’brient et al. [40]. The measurements reproduced here were done by Roger O’brient of Berkeley and Jen Edwards of UCSD.

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| Band | Lens Diam. | \( D/(f \times \lambda) \) | Resol. | #pix | #bolo | Spill. Eff | taper (dB) | Load (pW) | NEP_phon | NEP_poiss | NEP_total | NET_RJ | NET_CMB | NET_total |
|------|------------|----------------|-----|------|-------|-----------|-----------|----------|-----------|------------|-----------|--------|---------|-----------|
| 30   | 25         | 1              | 124 | 42   | 84    | 0.45      | -3        | 0.22     | 3.66E-18  | 2.95E-18   | 4.70E-18  | 74     | 75.4    | 8.21      |
| 40   | 25         | 1.33           | 95  | 42   | 84    | 0.55      | -4        | 0.28     | 4.10E-18  | 3.62E-18   | 5.60E-18  | 54     | 56.2    | 6.11      |
| 50   | 25         | 1.67           | 79  | 42   | 84    | 0.8       | -6        | 0.36     | 4.70E-18  | 4.90E-18   | 6.79E-18  | 36     | 38.3    | 4.17      |
| 65   | 25         | 2.17           | 64  | 42   | 84    | 0.92      | -10       | 0.42     | 5.09E-18  | 6.05E-18   | 7.91E-18  | 28     | 31.3    | 3.4       |
| 85   | 25         | 2.83           | 53  | 42   | 84    | 0.97      | -16       | 0.45     | 5.23E-18  | 7.12E-18   | 8.83E-18  | 23     | 27.4    | 2.98      |
| 110  | 10         | 1.47           | 35  | 243  | 486   | 0.75      | -5        | 0.34     | 5.23E-18  | 7.12E-18   | 8.83E-18  | 23     | 27.4    | 1.24      |
| 145  | 10         | 1.93           | 27  | 243  | 486   | 0.85      | -8        | 0.32     | 4.40E-18  | 7.80E-18   | 8.97E-18  | 15     | 26.2    | 1.19      |
| 190  | 10         | 2.53           | 23  | 243  | 486   | 0.95      | -14       | 0.24     | 3.68E-18  | 7.49E-18   | 8.35E-18  | 11     | 26.3    | 1.19      |
| 242  | 10         | 3.23           | 19  | 243  | 486   | 0.99      | -23       | 0.15     | 3.05E-18  | 7.01E-18   | 7.65E-18  | 7      | 26.1    | 1.18      |
| 314  | 10         | 4.19           | 18  | 243  | 486   | 1         | -38       | 0.07     | 2.07E-18  | 5.40E-18   | 5.79E-18  | 4      | 32.2    | 1.46      |
| Total|             |                | 286 | 2852 |       |           |           |          |           |            |          |        |         | 0.93      |

Table 3. Table of design parameters and sensitivity for a 30 centimeter crossed Dragone telescope using multichroic pixels with five frequency bands per pixel. The columns with units are: Central frequency of the band in GHz, the lens diameter in millimeters, the ratio of diameter to the product of \( f \times \lambda \), the number of pixels with the given band, the number of bolometers with the given band, the spillover efficiency through the Lyot stop, the edge taper in dB, the loading in pW, the Noise Equivalent Power (NEP) in W/√Hz, the photon noise NEP, the total NEP, the Rayleigh-Steel Noise Equivalent Temperature (NET) in µK√s, the CMB NET, and the total NET for all the bolometers at that frequency. The assumptions in this model are: focal ratio at feed = 2.5, diameter of focal plane = 26 cm, the diameter of the focal plane region used for the "high-frequency" pixels = 18 cm, the maximum theoretical area efficiency for a hexagonal close packed array = 90%, the efficiency assumed here = 75%, the telescope temperature = 2 K, the bolometer stage temperature = 100 mK, the bolometer temperature rise = 100 mK, optical efficiency to sky = 40%, optical efficiency to telescope = 30%, optical efficiency to 100mK = 30%, the fractional bandwidth for all bands = 30%, the ratio of saturation power to optical power = 4, and index of temperature dependence of the bolometer’s weak link = 1.

The edge taper determines the sidelobe level of the telescope, and it is therefore important to keep this number low. However, given the wide bandwidth of these pixels, a compromise of edge taper at the low-frequency end of the pixel has to be made with overall mapping speed for a fixed focal plane area at the high-frequency end. In this example, the low-frequency pixels are weighted toward efficiency at the higher frequencies and the high-frequency pixels are weighted toward good edge taper at the low-frequency end.
5. Conclusion

We do not anticipate that the optical coupling scheme will be a source of high technological risk for a CMB polarization space mission. The traditional approach using corrugated feeds can certainly be made to work well for single band pixels. Lens-coupled antennas and planar antennas are developing rapidly and may offer advantages in focal plane mass, system sensitivity, and complexity. The tradeoffs between these different approaches can be difficult to assess because they interact strongly with the system design. Demonstrations in ground-based and sub-orbital experiments are thus a critical step in assessing readiness for space.