Planar Antenna-Coupled Bolometers for CMB Polarimetry

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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.

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. 1. 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, $s < \lambda_{min}/2n$, where s is the spacing, λ_{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 $\sim\lambda_{min}/1.2n$. The size of the antenna, effectively the number of sub-antennas commbined, is determined by the desired beam width, $\Delta\theta \approx \lambda/d$.

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 [1], 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.

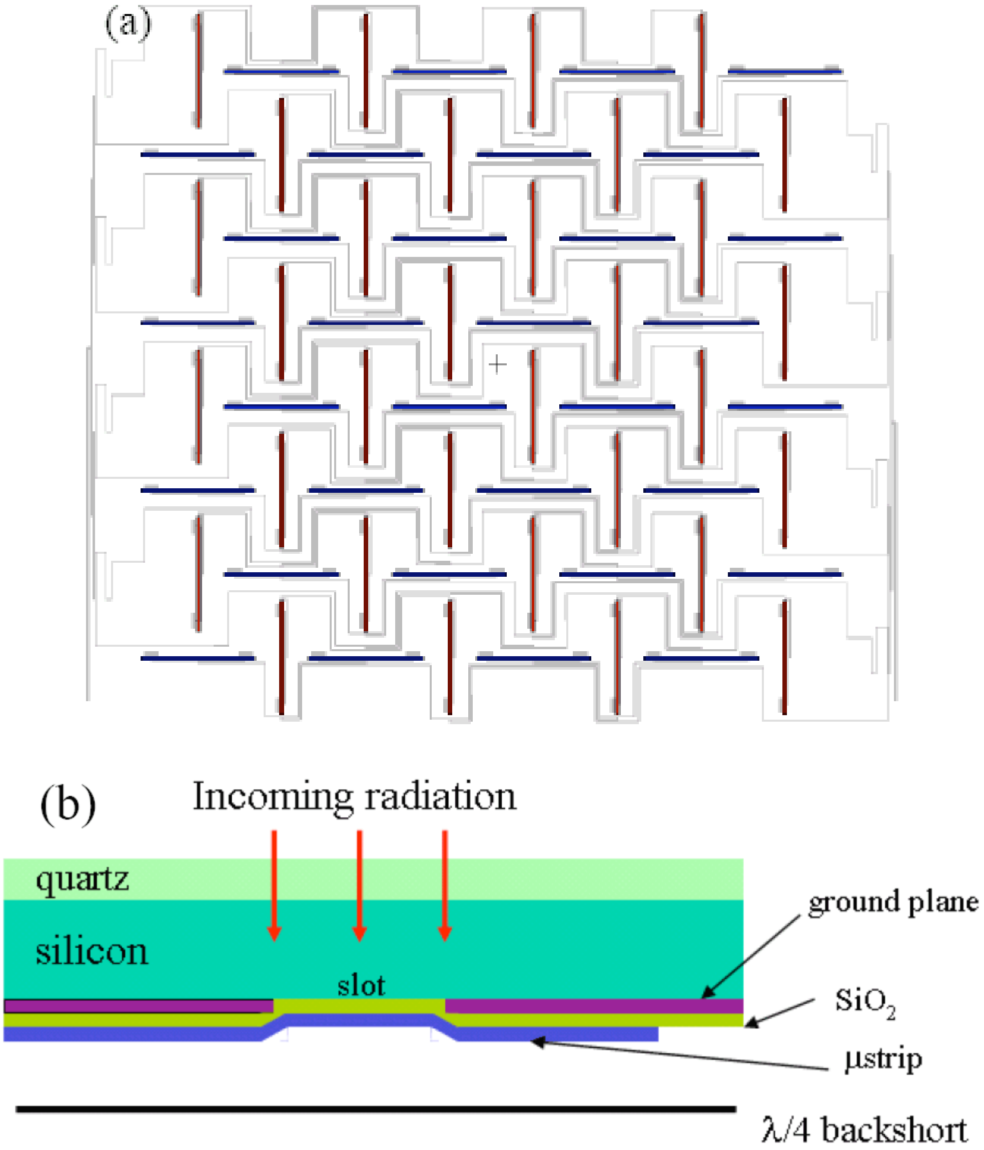

Fig. 1. Schematic of a planar antenna (a). The sub-antennas are slots (red and blue lines) combined by a microstrip summing network (grey lines). There are two antennas in this configuration which are closely interleaved, one in vertical polarization and one in horizontal polarization, and the slots and summing networks are independent. Actual antennas combine larger numbers of sub-antennas (see Fig. 2c) than shown in this illustration. The antenna is illuminated through the silicon substrate (b), with microstrip taps coupling to the slot antennas. A λ/4n layer of fused quartz serves as an anti-reflection coating. A reflective λ/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 $\sqrt{n}$ coating suffices, and, for devices made on Si, a tuned wafer of fused quartz is a highly efficient coating. Compared with lens-coupled antennas [2][3], 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 [4], 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 [5]. 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 [6].

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 $A\Omega$ product of the available focal plane is held constant [7]. 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 $2f\lambda$ 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 [8]. 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 [9].

3. State of Development

We have developed focal plane arrays of planar-antenna detectors [10] as shown in Fig. 2. 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 $\lambda/4n$ 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. 1, to better 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.

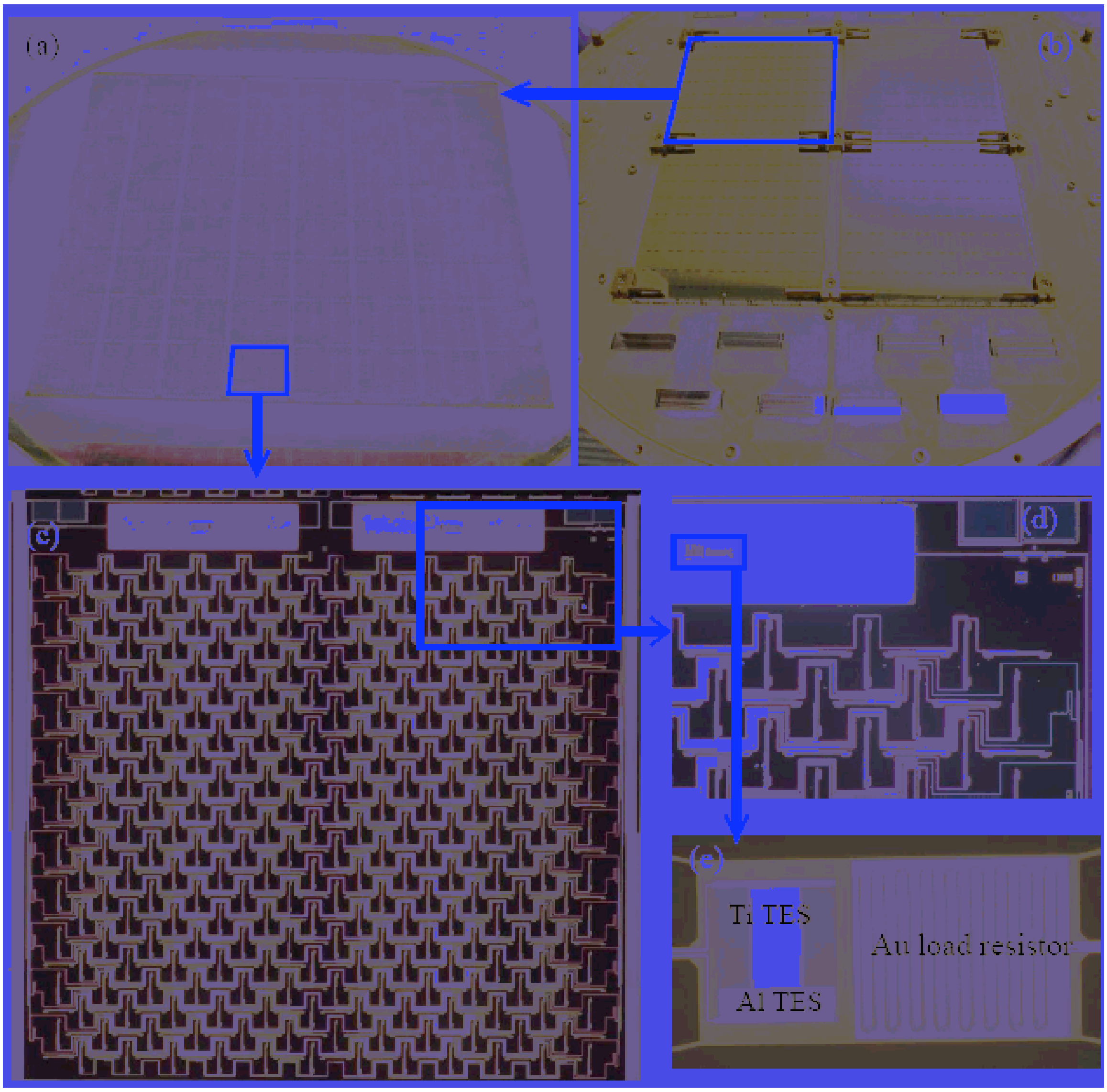

Fig. 2. (a) Focal plane array of planar antenna-coupled bolometers produced on a 100 mm wafer consisting of 64 antennas each with two TES bolometers measuring vertical and horizontal polarization. (b) A focal plane utilizing 4 such arrays with a total of 512 TES bolometers. The focal plane arrays are 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 [11][12]. 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 2fλ 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.

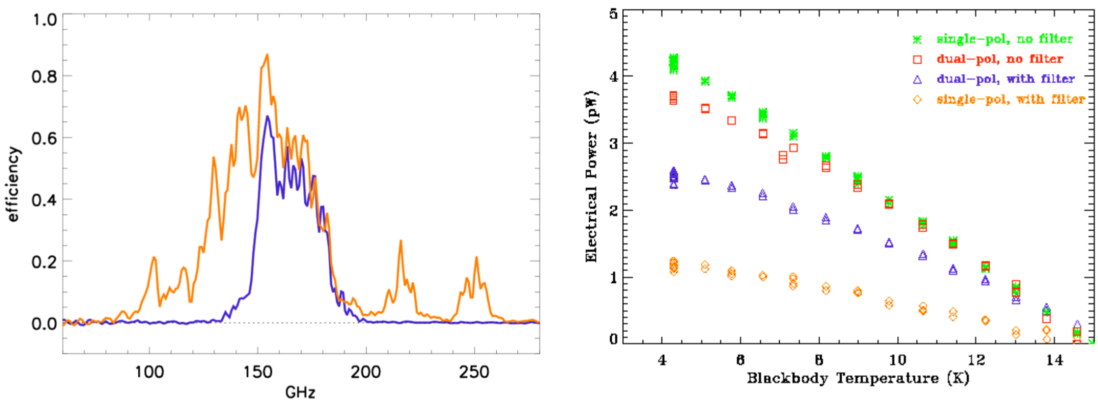

Fig. 3. (Left) Measured spectral response of an unfiltered (orange) and filtered (blue) antenna, including the quartz anti-reflection coating, antenna, combiner network, and meander absorber but not including the λ/4 backshort. The response curves are absolutely normalized by measuring the response to 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.

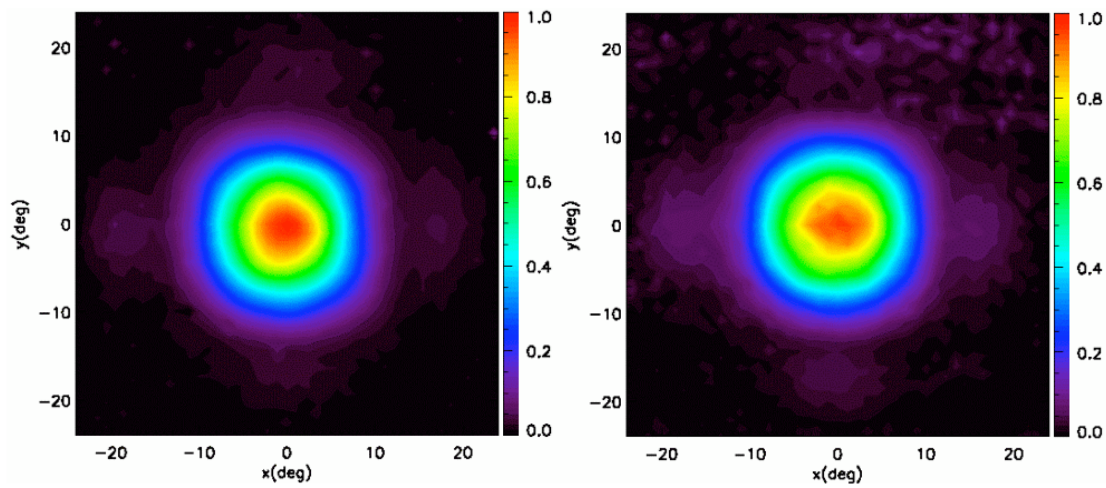

Fig. 4. Beam patterns of a filtered dual-polarization antenna in vertical and horizontal polarizations measured with a chopped thermal source. The original of the small deviations seen in the above panels are not clear, though we have seen evidence that reflections in the testbed windows and filters can effects at this level.

Measurements of full planar antenna-coupled TES bolometers are shown in Figs. 3 and 4. 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. 3 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 [13][14], typically 20 – 40 %. Using a $\lambda/4$ reflecting backshort will recover the ~10 % loss that the antennas radiate into the vacuum side of the device [15]. The beam patterns, measured with a chopped thermal source and shown in Fig. 4, 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. 2c 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 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 eliminate these defects.

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.

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. 2b) 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.

Table 1. Milestones Required to Demonstrate Technology Readiness for Space

Capability	**Advantage for CMBPOL**	**Technical Challenges**	**Milestone**
Attributes Necessary for CMBPOL			
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 at ≤ 30 and ≥ 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 Dual-polarization 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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