The Cosmology Large Angular Scale Surveyor (CLASS) Telescope Architecture

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***Abstract*—We describe the instrument architecture of the Johns Hopkins University-led CLASS instrument, a ground-based cosmic microwave background (CMB) polarimeter that will measure the large-scale polarization of the CMB in several frequency bands to search for evidence of inflation.**

***Index Terms*—antenna, propagation, measurement.**

I. INTRODUCTION

Observations of the cosmic microwave background (CMB) have greatly advanced our understanding of the history and ultimate fate of the universe. The ΛCDM cosmology asserts that the universe has expanded from a hot, dense state; cold dark matter in the early universe provided the seed for structure formation; and the universe is currently dominated by dark energy which is accelerating the expansion. Associated with our current understanding is the theory that the universe underwent a brief period of rapid expansion called inflation early in its history. Inflation has been invoked to explain the observed approximate homogeneity of the CMB, geometric flatness of the universe, and the origin of structure.

In addition to generating scalar perturbations, inflation is expected to produce a gravitational wave background that will polarize the CMB. This polarization would produce both curl-free “B-modes” and divergence free “E-modes” of polarization. The scalar perturbations only produce E-modes by symmetry, and thus measurement of the B-mode signal provides a clear test of inflation.

The Johns Hopkins University-led Cosmology Large Angular Scale Surveyor (CLASS) is an observatory designed to measure the polarization of the CMB to search for the B-mode signal. A detection would both confirm the theory of cosmic inflation and probe physics at its associated energy scale, currently predicted to be a trillion times higher than the maximum energy of the Large Hadron Collider.

CLASS is leading the current generation of experiments that is targeting the large angular scale signal that results from inflationary gravitational waves interacting with the reionized universe during the epoch in which the first stars formed. This signal peaks on large angular scales of the polarized angular power spectrum. This so-called “reionization bump” is valuable because this signal is uncontaminated by gravitational lensing that can twist the detected E-modes from the primordial density perturbation into B-modes at fine angular scales. In addition, the large angular scale coverage complements experiments operating at finer angular scales by providing an independent probe of inflation. Such a confirmation will be important in order to confirm the cosmological origin of any future fine scale primordial B-mode detection.

II. DESIGN CONSIDERATIONS

CLASS is an array of telescopes consisting of 4 receivers on two independent telescope mounts and will be deployed in the Atacama Desert. The 40 GHz telescope will consist of 36 dual polarization detectors and is scheduled to begin observing in 2014. Other telescopes will then be brought online. There will be two 90 GHz telescopes, each having ∼300 detectors each. The 4th telescope will ultimately contain ∼1000 detectors having channels at both 150 and 220 GHz.

The large number of detectors provides sufficient sensitivity to probe the large scale B-mode amplitude of $r < 0.01$. In addition, the multiple frequency bands are implemented to provide a means to extract the cosmological polarization from that of the Galactic polarized foregrounds consisting primarily of synchrotron emission from relativistic electrons and thermal emission from dust. The frequency channels were chosen to straddle the large-scale polarized foreground minimum which is anticipated at ∼70 GHz. Figure 1 shows the frequency bands of CLASS superposed on the atmospheric transmission of the Atacama site. CLASS will also be able to effectively utilize polarization data from PIPER [1] and Planck [2] at higher frequencies to further constrain the polarized dust foreground as well as C-BASS [3] for constraining synchrotron at lower frequencies.

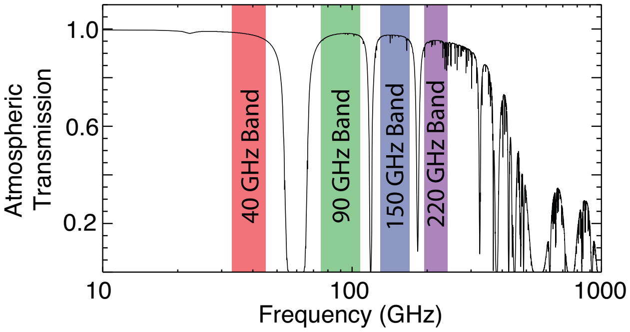

Fig. 1. The four CLASS bands are shown plotted on the atmospheric transmission from the Atacama Desert.

In order to measure the polarized angular power spectra at large angular scales, it is necessary to stabilize the instrument over disparate parts of the sky. The sky emission changes over both time and spatial scales, making it difficult to stabilize the instrument response with scanning alone. To this end, CLASS employs front-end rapid polarization modulation. The rapid modulation moves the signal band above the $1/f$ knee of the variations in the environment and the instrument. Modulating in polarization rather than by scanning allows independent measurements of the polarization state in each sky pixel and enables the large-scale survey. Recently, this general concept of rapid polarization modulation has been successfully demonstrated using a half-wave plate on the ABS experiment [4].

III. DETECTORS

A key enabling technology for CLASS is the detector architecture [5]. The CLASS detectors have been designed to maximize signal-to-noise while simultaneously controlling systematic errors. The detectors are feedhorn-coupled transition-edge sensor (TES) based devices that utilize microstrip circuits on monocrystalline silicon dielectric substrates. (See Fig. 2 for a schematic diagram.) A symmetric planar orthomode transducer (OMT) couples two independent orthogonal linear polarization modes from a feedhorn onto planar transmission lines over a broad (60%) bandwidth. The OMT consists of a set of microwave parts designed to separate the two linear orthogonal polarizations at the throat of the feed horn into a separate microstrip transmission lines. Each pair of waveguide probe antennas couples one orthogonal polarization onto a pair of microstrip lines that are differenced in a broadband magic tee [6] and coupled to a single microstrip line. This rejects the unwanted accessible waveguide modes above ∼1.4 f_{cutoff} and enables operation over a full waveguide band (∼60% in frequency). This is a planar variation on previous OMTs [7]. A fixed backshort is used to set the proper field phase and coupling of the waveguide antenna probes.

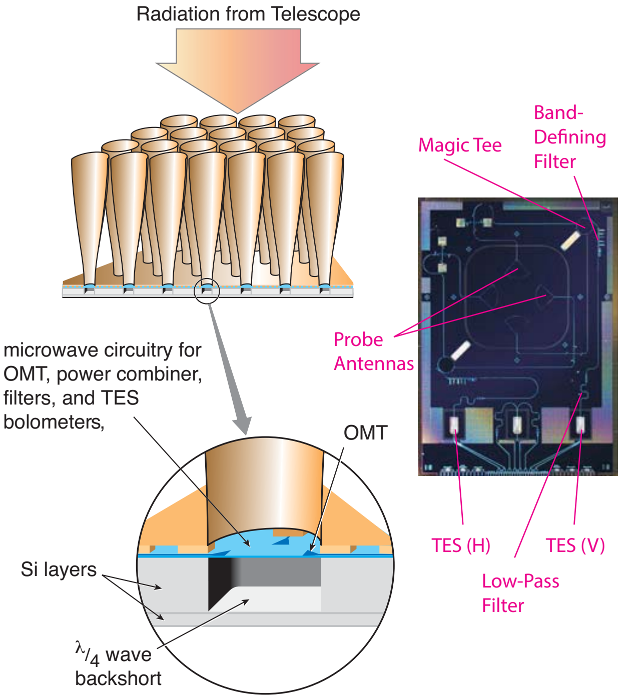

Fig. 2. The detector schematic is shown (left). Light from the telescope optics is incident on an array of feedhorns. A planar OMT couples the two orthogonal linear polarizations into independent microstrip transmission lines. Each signal is filtered and independently detected in a TES bolometer. A photo of one of the photolithographed 40 GHz chips is shown (right).

The bandpass of the OMT is shown in Figure 3. For CLASS, atmospheric lines and ground spill motivate a smaller bandwidth than that provided by the OMT. This signal band definition is accomplished via a combination of on-chip filtering [8] and effective integrated shielding of stray light (blue leaks). The integrated stray light control for the 40 GHz detector is achieved over a frequency ratio of > 10:1.

The monocrystalline silicon substrate that is used for the microstrip dielectric layer provides a highly uniform dielectric constant that results in reliable circuit uniformity and performance. In addition, the monocrystalline silicon enables high transmission efficiency due to its extremely low loss. Fabrication details for the 40 GHz devices have been reported [9], [10]. The feedhorns for CLASS are monotonic, smooth-walled devices with low cross-polarization response over a

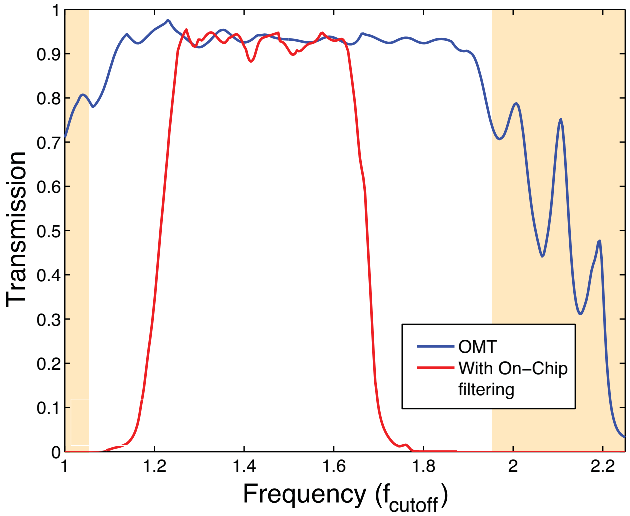

Fig. 3. The modeled response of the OMT (blue) and the CLASS (red) band are shown.

large bandwidth [11].

The efficiency of the devices, including all integrated filtering, has been measured to be ∼90% for each polarization in the 40 GHz devices. The 40 GHz devices have been fully demonstrated, and the corresponding 36-element array is currently being constructed. Prototype 90 GHz detectors have been fabricated and are currently being tested.

The detectors will be time-domain multiplexed using SQUID multiplexers and series arrays produced by NIST and read out using a Multi-Channel Electronics module produced by the University of British Columbia.

IV. OPTICS

The CLASS optics have been designed to accommodate the front-end polarization modulator which is the first element in the optical system. A diagram of the 40 GHz system is shown in Figure 4. The higher frequency focal planes will be have identical warm optics, with small adjustments to the cold optics (such as in feedhorns and antireflective coatings for the lenses). Light from the sky is incident on the VPM. A pair of ambient-temperature mirrors reimage the VPM pupil at a cold stop inside of the cryostat. A pair of anti-reflection-coated high-density polyethylene lenses focus the radiation onto the feedhorns at the front of the focal plane. The optics are discussed in detail elsewhere [12]; however, it is worth mentioning a few key points here that highlight the uniqueness of this telescope. First, it is desirable to place the modulator at a pupil. Generally, this is good practice, as this sets the illumination of the modulator by all detectors to be identical. In the VPM case, this is also preferred because the small (wavelength-scale) translations do not produce a pointing shift when located at a pupil. In order to reduce possible systematic errors due to variable illumination of the VPM, care was taken to ensure high fidelity reimaging of the cold stop so as to limit VPM illumination to the central ∼40 cm of the 60 cm diameter aperture.

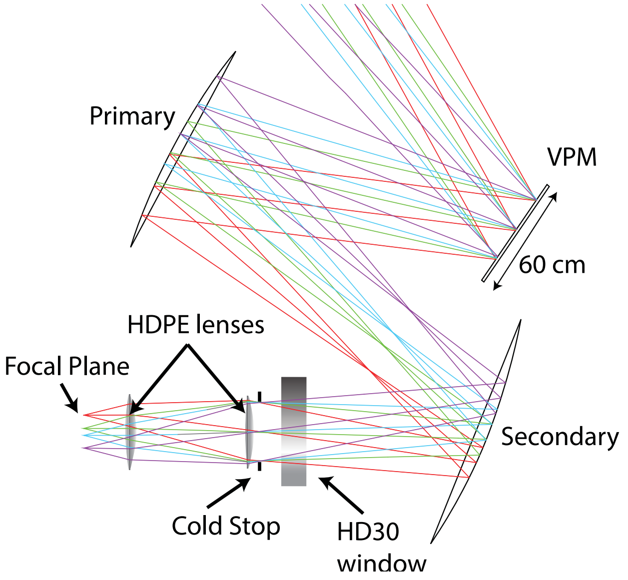

Fig. 4. The optical path of one of the CLASS receivers is reproduced from [12]

Another driving factor in the optics was the desire to maximize the efficiency per detector. The 40 GHz telescope has a high (> 0.996) Strehl ratio over the field of view of the receiver. In addition, the focal plane is matched to an f/2 beam. With the feed horn patterns employed for the 40 GHz focal plane, a cold pupil edge taper of ∼-10 dB is achieved. For this design, such an illumination allows more than 80% of the power from the detector mode to reach the sky while maintaining control of the illumination of the VPM.

V. POLARIZATION MODULATION

To achieve the stated science goals, CLASS employs a novel front-end modulator, known as a Variable-delay Polarization Modulator (VPM). Similar devices are being implemented on PIPER [1]. The VPM consists of a polarizing grid positioned in front of and parallel to a movable mirror. As the grid-mirror distance is varied, the phase delay between two orthogonal linear polarizations is modulated, resulting in modulation given by

$$Q' = Q\cos\phi + V\sin\phi, \qquad (1)$$

where ϕ is the phase delay introduced by the grid-mirror separation [13], [14]. The polarization transfer function of the VPM is shown graphically in Figure 6 as a rotation on the Poincaré sphere in the $Q-V$ plane. Because the intermediate state of the modulation cycle is circular polarization, residuals in the polarization transfer function mix Stokes Q and V, rather than Q and U as in a half-wave plate [15]. This control of the polarization angle helps to reduce $E \rightarrow B$ mixing.

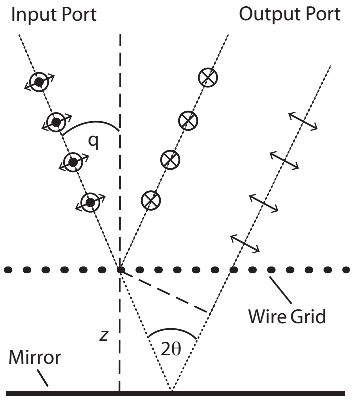

Fig. 5. The VPM consists of a polarizing grid placed in front of and parallel to a moving mirror. As the grid-mirror distance changes, the polarization transfer function is modulated.

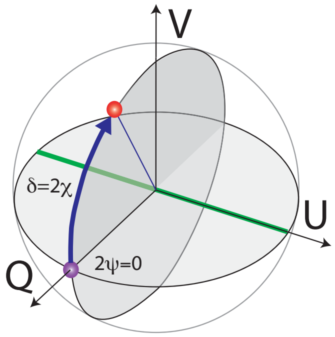

Fig. 6. The VPM transfer function is shown as a rotation on the Poincaré Sphere.

One advantage of the VPM is that it can be made large enough to be placed at the primary pupil of the instrument while simultaneously providing a rapid enough ($\sim$10 Hz) motion so that the primary modulation can occur in polarization. The front-end placement is important in separating the polarized signal from the (dominant) unpolarized background because the polarization signal from the sky can be encoded before the instrument can alter the signals polarization state.

The VPM polarization transfer function for prototype VPMs has been measured and shown to be well-described using a transmission line model [14], [16].

VI. SUMMARY

The CLASS instrument has been designed to measure the large scale polarization of the CMB to test cosmic inflation. Specifically, the telescope design has been driven by the the implementation of the VPM for fast front-end polarization modulation and high-efficiency detectors.

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