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A large angular scale CMB polarization experiment for Dome-C [⋆]

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Abstract. The Cosmic Microwave Background Radiation (CMBR) can be completely characterized by specifying its frequency spectrum as well as its spatial anisotropy and polarization spectra. After robust detections obtained by many experiments - COBE and WMAP satellite in particular - we are now looking towards a detection of the B-modes in the CMB polarization. This is a huge experimental challenge as the signal is incredibly weak (from zero to 1 part in 10 million). A detection of these elusive B-modes, however, will represent an indirect detection of the long-wavelength primordial gravitational wave background. In this paper we present a possible instrument capable, in principle, of detecting the B-modes.

Key words. Cosmic Background Radiation – Interferometry – Polarization

1. Introduction

Over 20 years of experiments dedicated to the measurement of the CMB spectrum and anisotropy, culminated with the COBE and WMAP satellite experiment, have now established inflation and cold dark matter models as the favored theory describing the early universe. The Planck satellite will characterize the temperature and polarization auto and cross correlation power spectra (<TT>, <TE>, <EE> and marginally <BB>) to a high degree of accuracy. Detection of the tensor (B-mode) component of the CMB polarization would constitute an observation of anisotropy structure imprinted on the CMB by primordial ultra-long wavelength gravitational waves. This detection will give information about the energy scale of inflation, together with the physics of Grand Unification and the nature of the inflaton field. This is one of the few ways in which theories of fundamental physics at high energies can be tested. In preparation for a post-Planck

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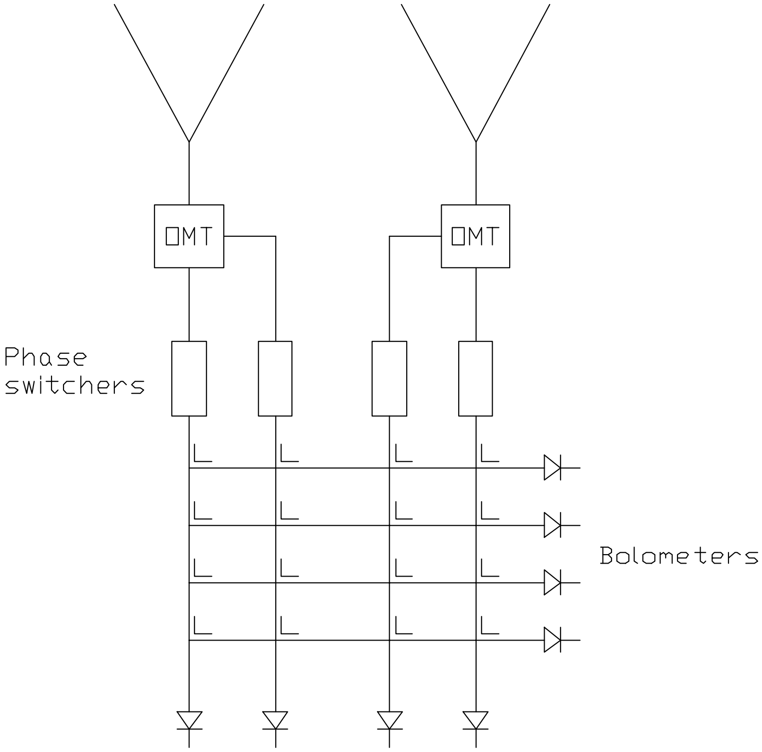

Fig. 1. Example of a 2-element adding interferometer. The 4 bolometers at the bottom measure the total power. Each bolometers on the right measures the square of the x and y linear polarization amplitudes $\frac{1}{n}(E_{1x} + E_{1y} + E_{2x} + E_{2y})^2$. If each phase switcher modulates at a different frequency, the resulting n(n-1)/2 beating frequencies uniquely identify each baseline. The directional couplers have to be properly balanced to equalize the phase and amplitude of each input signal at the output ports (Pisano, G. et al., (2003))

satellite dedicated to a full-sky map of the B-mode signal, it is very important that researchers start to design experiments potentially sensitive to the B-mode signal. In order to extract this extremely low signal, many order of magnitudes weaker than the CMB <TT> signal, many technological and scientific issues need to be addressed. Instrumental effects, for example, need to be understood and minimized to an unprecedented level by a combination of careful design and experimental trials. In order to properly design the instrument we need to know the expected level of the signal and potential contaminants. This information drives the choice of the detectors, and fixes the acceptable level of random and systematic noise. The relative strength of the B-mode signal is fixed by the tensor-to-scalar ratio r, i.e. the ratio between the amplitudes of the primordial tensor and scalar fluctuations. Unfortunately, there is no *a priori* theoretical indication of the level of the B-mode signal and we currently rely on an upper limit from the WMAP (Bennett, C. L., et al, (2003)) mission: $r < 0.71$ at 95% c.l. Gravitational lensing, unfortunately, transform E-modes into B-modes and can be regarded as a contaminant, although of extraordinary interest in itself.

The weak gravitational lensing signal limits the detectability to r ~ 0.001. The best approach is therefore to design an experiment that will be capable of detecting the weak gravitational lensing signal. We propose the realization of a large angular scale polarization experiment potentially sensitive to the minimal B-mode signal to be installed on the best observing site available today: Dome-C. The proposed experiment is based on a combination of old proved technologies like sub-K bolometric detectors and interferometric techniques. We believe that the combination of these technologies will allow the construction of a polarimeter with unprecedented low instrumental effects

2. Bolometric Interferometry

Two types of detection schemes are used at mm and sub-mm wavelengths: coherent (HEMT amplifiers or SIS mixers) and incoherent (bolometers). In the first case the amplitude of the e.m. wave is amplified and then detected. The amplification device preserves the phase of the e.m. field. In the second case, the phase information is lost in the detector which is sensitive to the power of the e.m. wave. Bolometric system are preferred when the signal is broadband and high frequency. In these conditions today we have the technology to build bolometers with intrinsic noise less than the photon noise of the CMB. Coherent detectors, on the other hand, have been used in interferometers from the ground for observing the CMB and diffuse emission. It is common knowledge that interferometric techniques are powerful for their imaging capabilities. Quite a number of interferometers have been and are in use for detecting CMB anisotropy and polarization (for example DASI, CBI and VSA).

The B-mode experiment is an adding interferometer that uses cooled bolometers as detectors. The idea is to take advantage of the combination of two well established technologies to make a high sensitivity map of a fraction of the sky with a high degree of immunity to instrumental and atmospheric systematics. The mapping of the sky at millimeter and sub-millimeter wavelengths depends on the type of detector one uses. Single dishes with either coherent or incoherent detectors typically use some form of "chopping", either by nutating a secondary mirror or by steering the entire primary at a rate faster than the 1/f noise in the atmosphere and detectors. Similar approaches are used with arrays of detectors or receivers. In order to form a 2D map, which can be used to compare signals from both adjacent and distant pixels, the scanning method must move the beam (or beams) around on the sky at a rapid rate. 1D scans at constant elevation help reduce atmospheric effects, but make 2D mapping difficult. Another method, pioneered by the SuZIE array - and more recently successfully used by BOLOCAM - is to use an array of matched detectors and form differences in signals electronically. Drift scanning increases the field of view. Interferometry, until now only possible with coherent receivers at these wavelengths, offers a variety of advantages over these scan methods: it allows direct 2-D imaging; directly measures Fourier transform (visibility) of the sky brightness; reduces effects of atmospheric fluctuations in ground-based observations; allows high angular resolution without large, expensive single dishes; eliminates rapid mechanical chopping.

2.1. 2-elements adding interferometer

In a simple 2-element radio interferometer, signals from two telescopes aimed at the same point in the sky are multiplied (correlated) so that the sky temperature is sampled with an interference pattern with a single spatial frequency. The output of the multiplying interferometer is the visibility

$$V(\boldsymbol{u}) \propto \int d\hat{x} G(\hat{x}) \Delta T(\hat{x}) e^{2\pi i \hat{u}\cdot\hat{x}}$$

where $\hat{x}$ is a unit 3-vector in the direction of points on the sky, G($\hat{x}$) is the beam pattern of each antenna (assumed to be iden-

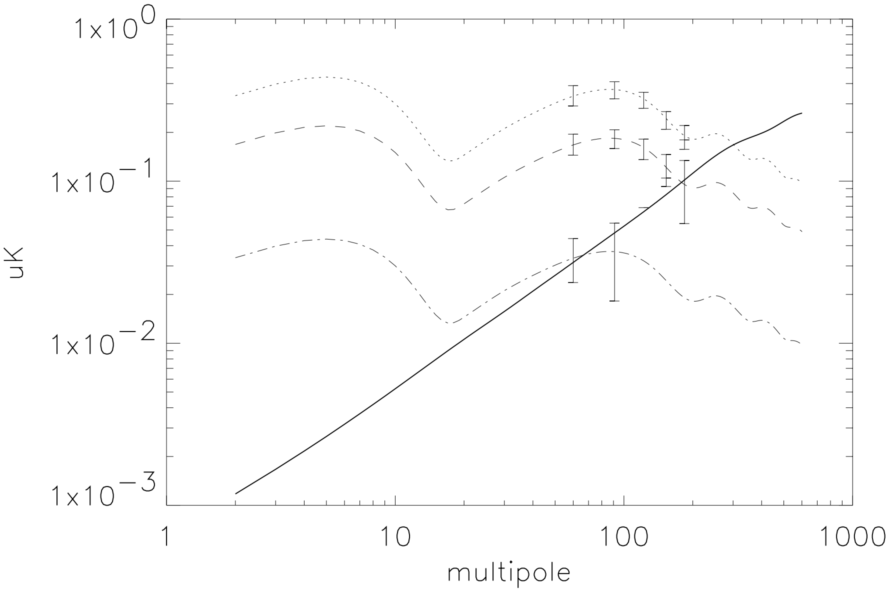

Fig. 2. The predicted sensitivity of the proposed experiment. The dotted curves represent the CMB polarization B-mode signal for 3 different choices of the tensor to scalar ratio. From top to bottom they are respectively r=0.1, 0.05, 0.01. The continuous line is the predicted gravitational lensing signal.

tical), $\Delta T(\hat{x})$ is the map of temperature fluctuations we are trying to measure on the sky. $\boldsymbol{u}$ is a vector oriented along the baseline with length B/λ. $\Delta T(\hat{x}) \propto E_0^2$. To recover the full phase information, complex correlators are used to measure simultaneously both the in-phase and quadrature phase components of the visibility. The electric field wavefronts from two telescopes are added and then squared in a detector (an "adding" interferometer as opposed to a "multiplying" interferometer Rohlfs, K. and Wilson, (1996)). The result is a constant term proportional to the intensity plus an interference term. If we phase chop one of the two arms of the interferometer, a phase-sensitive detection at this modulation frequency recovers both the in-phase and quadrature phase interference terms. We recover the same visibility as for the multiplying interferometer. The four Stokes parameters can be recovered, in principle, if we extract and correlate the two linear polarization E_x and E_y by using suitable circuitry. Fig. 1 shows a more general use of all the linear polarization amplitudes. Each linear component is switched at a different frequency.

3. Sensitivity

It is interesting to try to estimate the sensitivity of bolometric interferometer compared with a "standard" heterodyne interferometer or a bolometric array. The fundamental problem of bolometric interferometry is that the low noise component (the detector) is at the end of the optical chain. This means that the attenuation along the chain must be limited to the minimum. Similar care has to be applied in more standard bolometric arrays although the optics can be simpler. Heterodyne interferometers are less sensitive to this prob-

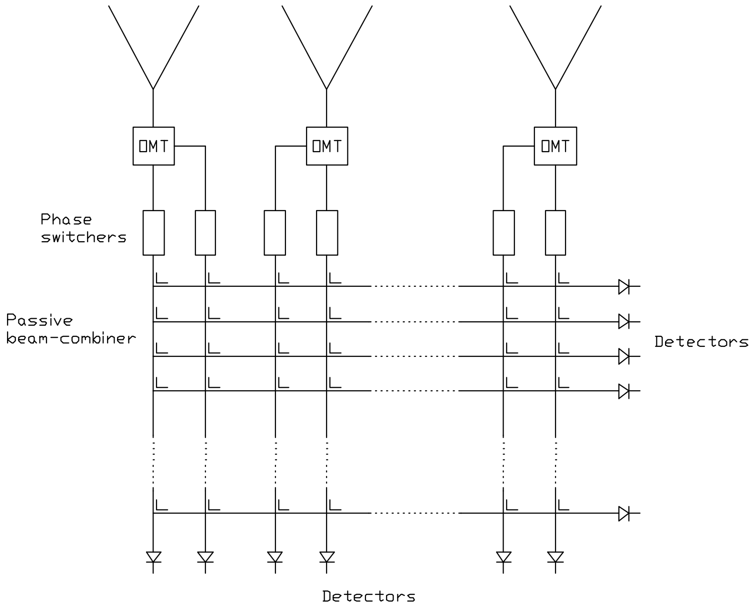

Fig. 3. Schematic view of a n-element adding interferometer. The proposed Dome-C experiment consists of an array of 16 x 16 compact horn array. The number of output lines in this instrument will be 512 when we consider the two polarizations.

lem providing that the amplification element (HEMT amplifier before or after the mixer element) is located as close as possible to the horn. In order to carry out the beam combination in bolometric interferometers we also have to divide the optical power from the horns/antennas by N (number of horns/antenna) in order to create all the cross and auto-correlation products. Although these might look like formidable problems, it turns out that there are substantial advantages of using cooled bolometers under certain conditions. Following Zmuidzinas J. (1998) and Zmuidzinas J. (2003), the background limited sensitivity of a bolometric detector receiving a diffraction limited beam single polarization is expressed by:

$$\sigma_P^d = \frac{h\nu}{\sqrt{\Delta\nu\;\tau}}\sqrt{\frac{n_0\left(1+\eta^d n_0\right)}{\eta^d}}\;\Delta\nu$$

where η is the effective quantum efficiency (including optical losses), τ is the integration time, $\Delta\nu$ is the optical bandwidth and n_0 is the mean photon occupation number given by:

$$n_0 = \frac{\epsilon}{e^{\frac{h\nu}{kT}}-1}$$

ϵ is the total emissivity of the background. The corresponding expression for a coherent detector is:

$$\sigma_P^c = \frac{h\nu}{\sqrt{\Delta\nu\,\tau}}\frac{1}{\eta^c}\left(1+\eta^c n_0\right)\,\Delta\nu$$

Thermal emission from the optics inside the instrument has been neglected in both cases. In the case of a bolometric interferometer we have to include the effect of the beam splitting and so the sensitivity *per baseline* is:

$$\sigma_P^{\text{int}} = \frac{h\nu}{\sqrt{\Delta\nu\,\tau}}\sqrt{\frac{n_0\left(1+\frac{\eta^d n_0}{m}\right)}{\frac{\eta^d}{m}}}$$

where m is the number of horns or antennas. It is now possible to compare the various sensitivities by building a table of ratios. For a reasonable choice of experimental conditions and at frequencies higher than around 100 GHz, the bolometric interferometer is better than a heterodyne interferometer. The sensitivity of a bolometric interferometer, under some assumptions like compact configuration of the optical elements, tends to be equal to an *ideal* array of bolometric detector in total power. In a future paper we will discuss the details of the sensitivity calculation.

4. The proposed experiment for Dome-C

The design that we propose is based on a calculation of the minimum "detectable" signal coming from weak gravitational lensing. In this case, even if the B-mode signal is zero, we are guaranteed to at least detect the B-mode signal induced by lensing. Assuming a winter-over experiment from Dome-C (50% observing efficiency) where the detectors are limited by the photon noise of the atmosphere, we show that a bolometric interferometer with about 20,000 baselines is required. Fig.2 shows the results of such a calculation. The 20,000 baselines are achievable by combining the light collected from the 256 horns proposed interferometer. The primary beam is determined by the main beam of each horn. In our case we propose to use dual-polarization corrugated horns with a Full Width Half Maximum beam of 7 degrees. The polarization split will be achieved by an Ortho-Mode Transducer (OMT). Fig. 3 shows the conceptual design of such an experiment. The detector choice is dictated by the background noise (mainly photon noise from the atmosphere) and post-detection bandwidth. Virtually every detector contains all the 20,000 beating frequencies corresponding to each baseline. This forces us to either use a fast detector or reduce the number of phase-chopping frequencies. In order to accommodate so many frequencies in the electrical bandwidth and be able to successfully characterize (and sample) each one, we predict we will need a detector with an electrical bandwidth of about 1 to 10 MHz. This requirement immediately precludes the usage of standard bolometers (like spider-web with NTD) because of their extremely limited time constant (just around few msec). Available choices are: Transition Edge Superconductor (TES) detectors; Hot Electron Bolometers (HEB); Superconductor-Insulator-Superconductor (SIS) direct detectors. We are currently exploring these alternatives. The final experiment will be composed of 3 independent cryostat each equipped with a 256 dual-polarization horns arranged in compact array configuration. Each interferometer will work at a different frequency: 90, 150 and 220 GHz with a bandwidth of about 20%. Three frequencies are needed for component separation. Additional in-band spectroscopy - into 3 or 4 channels - will be achieved in each interferometer by using strip-line bandpass filters in front of the detector.

5. Conclusions

Quite a number of issues need to be addressed in order to optimize the design of the proposed experiment. In addition to the detector technology, we need to design, realize and test cryogenic, low-loss, wide-band phase switchers. The waveguide multi-port passive beam-combiner is currently under design and simulation phase. Various intrinsic systematic effects are being considered like, for example, cross-talk and cross-polarization effects in the horns, as well as phase matching in the front-end electronics. The effect of the cryostat window is also very important. We are currently evaluating the possibility of equipping each individual horn with its own vacuum break. It is very important that wavelength dispersion in the microwave components be reduced to a minimal level because it translates directly into a loss of sensitivity. However, we believe that all these (and other) effects can be properly modelled resulting in an instrument that is far superior in performances to any array of direct detector instrument designed for CMB polarization studies

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