Detectors for the South Pole Telescope

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Abstract

The South Pole Telescope (SPT) is a 10-m mm/sub-mm telescope at the Amundsen-Scott South Pole Station. It’s primary science goals consist of a galaxy cluster survey for understanding Dark Energy and probing the physics of Inflation through the CMB polarization. Both science goals require exceptional sensitivity necessitating focal planes with many optical elements. The focal planes of the SPT utilize Transition Edge Sensor (TES) bolometers to build arrays of nearly 1000 detectors. In this talk, I will present the TES bolometer technology for both the first SPT focal plane and its upcoming upgrade to a polarization sensitive array.

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1. Introduction

Recent developments in mm-wave detector technology are driving the frontier of Cosmic Microwave Background (CMB) observations. Current and upcoming CMB experiments promise new insights into the nature of Dark Energy, neutrino mass, and Inflation. [1, 2, 3]

The South Pole Telescope (SPT) [4, 5] is a 10-m-diameter off-axis telescope located at the Amundsen-Scott South Pole station in Antarctica which is one of the best sites for mm-wave observations [6]. The SPT is a telescope optimized for high resolution observations of low surface brightness phenomena having arcminute resolution at $\lambda = 2$ mm, low scattering, and a wide field of view ($\sim 1$ deg$^2$).

The SPT has two key projects. The first is called the SPT-SZE, a galaxy cluster survey utilizing the (thermal) SZ effect [7, 8]. The SZ effect is a small spectral distortion of the CMB caused by the inverse Compton scattering of the background photons off the hot (10 keV) intracluster gas in clusters of galaxies. The beauty of the SZ effect is that its observed brightness is independent of distance. To first order, an SZ-survey therefore produces a distance independent, mass-limited cluster catalog which can be used to constrain the properties of Dark Energy. [1, 9, 10] By the end of 2011, the SPT-SZE would have completed its survey of 2500 deg$^2$ after which the second key project, SPTpol, will begin observations. SPTpol involves a new polarization sensitive focal plane which will measure the CMB polarization. The polarization of the CMB is useful for constraining the mass of neutrinos [2] and is also the unique probe of the energy scale of Inflation. [3] The focal planes for both of these projects utilize new Transition Edge Sensor (TES) bolometers with frequency-domain SQUID multiplexing.

2. Transition Edge Sensor Bolometers

TES bolometers [11, 12] are the chosen technology for both the SPT-SZE and SPTpol focal planes. Each detector consists of a primary heat capacity, $C$, which is heat sunk to a thermal bath via a weak thermal conductance, $G$. Radiation is directly absorbed and thermalized in $C$ producing a change in its temperature. Measuring the temperature change thus corresponds to a measurement of the change in absorbed power. These TES bolometers are an example of detectors that measure the thermal dissipation of directly absorbed photons; details of such detectors are throughly described elsewhere (eg: [13, 14, 15]).

For these bolometers, changes in the absorbed power are measured by a Transition Edge Sensor (TES) consisting of a thin film superconductor voltage-biased into the transition region between its normal and superconducting states. In this state, the detector experiences strong negative Electro-thermal feedback (ETF) [16]. As discussed in [12], the bolometer’s current responsivity (the change in current per change in absorbed power) is

$$S_I \sim \frac{1}{V_b} \quad (1)$$

where $V_b$ is the voltage bias across the TES. Electro-thermal feedback changes the effective time constant from the intrinsic thermal timeconstant, $\tau_0 = C/G$, to

$$\tau_{ETF} = \frac{\tau_0}{L + 1} \quad (2)$$

where

$$L = \alpha \frac{P_b}{G T_c} \quad (3)$$

is the equivalent “loop” gain with $\alpha = \frac{d\log R}{d\log T}$ being a measure of the steepness of the TES $R(T)$ curve, and $P_b$ being the electrical bias power. The strong negative electro-thermal feedback improves the linearity of the detector response and increases the detector bandwidth.

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Noise for the detectors is typically referred to equivalent power absorbed by the bolometer or Noise Equivalent Power (NEP). There are three contributions to the detector noise. The first contribution comes from the random fluctuations of the photons arriving at the detector. The second contribution corresponds to thermal fluctuations of the phonon carriers which comprise the bolometer $G$. The last contribution is from the readout electronics. The statistical photon fluctuations constitute the irreducible physical background. As such, nearly background limited performance is achieved when these three contributions are nearly equal. For the SPT, the background limited NEP is $\sim 50 \text{ aW Hz}^{-1/2}$.

3. Frequency-domain SQUID Multiplexing

TES bolometers are low impedance devices biased with nearly constant voltage. Strong ETF relates changes in TES current linearly to changes in absorbed power. The current through the TES is measured by a Superconducting QUantum Interference Device (SQUID) [17] series array amplifier. To readout a large focal plane array composed of nearly 1000 bolometers, SPT employs a frequency-domain SQUID multiplexer (fMUX). [18] In this multiplexing scheme, detectors are biased with a high frequency signal (350–1000 kHz) with separate detectors connected in series with a unique resonant LC filter. Each filter defines a narrow band ($\sim 10–16$ kHz FWHM) for each TES centered at individual resonant frequencies for each SQUID. The individual unique TES-LC circuits are then summed together and readout by a single DC SQUID array. Figure 1 shows a circuit diagram illustrating the fMUX scheme.

The electrical bandwidth of the filters in the fMUX must be considered when designing the thermal circuit of the TES bolometers. [19] If the electro-thermal time constant, $\tau_{ETF}$ (see eqn. 2), is comparable to the electrical time constant ($L/R$), the system becomes unstable. [20] For the TES bolometers used by SPT, the thermal circuit is tailored to the available electrical bandwidth through the use of a Bandwidth Limiting Interface Normally made of Gold (BLING) which must be sufficiently well coupled to the TES. [19]

4. Detectors for SPT-SZ

The detectors for SPT-SZE are TES spiderweb bolometers [21, 22] fabricated at the UC Berkeley Microlab and are shown in fig. 2. Radiation is absorbed by a Au spiderweb suspended on SiN. The primary heat capacity is a Au BLING at the center of the spiderweb. The temperature is measured by an Al-Ti TES located near the BLING. $G$ is defined by a Au bar from the center of the suspended web to the Si substrate which serves as the heat sink. The detectors are fully lithographed and manufactured in wedge shaped arrays.
Each detector couples to the telescope through an array of smoothwalled conical feedhorns (see fig. 3 left). The feedhorn includes a section of waveguide which defines the lower edge of the optical passband. The upper edge is defined by a set of free-space metal-mesh filters (see fig. 3 right). [23] Each wedge observes in one of three passbands centered at 90, 150, and 220 GHz with $\sim$30–40 GHz bandwidth. The entire SPT-SZE focal plane consists of six wedges for a total of 960 possible optical detectors.

![Fig. 2. Left: image of a SPT-SZE wedge of TES spiderweb bolometers. Center: image of a single bolometer. Right: close-up of the central region of the bolometer showing the BLING and the TES.](image)

![Fig. 3. Left: an SPT-SZE wedge showing the detector array, LC filter board, and feedhorn array. Right: image of the full SPT-SZE focal plane with the feedhorns covered by free-space metal-mesh filters.](image)

5. Detectors for SPTpol

The SPTpol focal plane will observe in two optical passbands; one centered at 95 GHz, the other at 150 GHz. Similar to SPT-SZE, the bandpasses are defined by metal mesh filters and waveguide cutoffs to provide $\sim$36 GHz of optical bandwidth. Separate detector technologies are being utilized for each of the passbands.

The schematic of the SPTpol focal plane is shown in fig. 7. The inner $\sim$160 mm will be filled with the 150 GHz detectors. The outer portion of the focal plane will be filled with the 90 GHz detectors. This layout was chosen to maximize the best performance of the SPT optics which begins to degrade at $\sim$160 mm for 150 GHz but continues to perform well out to $\sim$240 mm for 90 GHz.
At 90 GHz, SPTpol will utilize detectors developed and fabricated at Argonne National Lab (ANL). [24, 25] In the ANL detector architecture (shown in fig. 4), one of the two linear polarization TE11 waveguide modes couples to a lossy Pd-Au dipole absorber suspended in the center of the waveguide cavity by a SiN bridge. The bridge serves both to hold the absorber in the waveguide cavity and to define the $G$ for the bolometer. The change in absorber temperature is measured with a Mo-Au TES coupled to Pd-Au BLING. The strength of the electrol-thermal feedback is controlled by tuning the profile of the R(T) superconducting transition using Nb structures patterned on the TES. Both linear polarization modes are measured by crossing two detectors in orthogonal orientations. Each 90 GHz pixel consists of a crossed pair of detectors and couples to the telescope through a contoured smoothwalled feedhorn. [26] This detector design has demonstrated high coupling efficiency, low cross-polarization, stable electro-thermal operation, and low-noise. [27] There will be 188 individual 90 GHz pixels mounted around the perimeter of the SPTpol focal plane (as shown in fig. 7). Each pixel is approximately 10.1 mm in diameter which is easily machined and is nearly optimal for array mapping speed [28] while minimizing pixel-to-pixel crosstalk. The pixels are individually assembled by hand, which is tedious but feasible for 188 modules.

At 150 GHz, the best detector size and spacing for optimized array performance [28] is too small for conventional machining. As such, arrays of detectors are the preferred technology at this wavelength. SPTpol will use detectors fabricated at the National Institutes for Standards and Technology (NIST). [29] In this architecture (shown in fig. 5), a Nb Ortho-Mode Transducer (OMT) [30] feeds one of the two TE11 polarizations onto Nb microstrip which is terminated by lossy Au suspended on a SiN island. The temperature of the island is measured by an Al-Mn TES with Pd-Au BLING and $G$ for these bolometers is defined by the SiN legs of the island. The OMT couples the two polarization modes onto two separate bolometers. The 150 GHz detectors are fabricated as a hexagonal array of 84 pixels which will be mounted in the center of the focal plane where the 150 GHz optical performance remains good. Since the detectors are fabricated as arrays, care must be taken to minimize pixel-to-pixel crosstalk. Additionally, micromachining techniques need to be employed to manufacture an appropriate feedhorn array. Both of these challenges have been addressed and each detector array couples to the telescope through a corrugated feedhorn built from stacked micromachined Si platelets (see fig. 6). [31]. Chokes in the feedhorns minimize potential pixel-to-pixel optical coupling.

In addition to standard celestial calibration methods (eg: galactic HII regions and the CMB temperature anisotropy), SPTpol will also need to determine the polarization angle of each pixel. This calibration will be performed through a special polarized source on a tower in the far-field of the SPT.
Fig. 5. Left: image of a single NIST pixel. A planar Ortho-Mode Transducer (OMT) is used to couple the individual linear polarizations of the TE11 waveguide mode onto separate TES bolometers. Each bolometer is an isolated SiN island whose temperature is measured by an Al-Mn TES. Radiation from the OMT is fed to each island via Nb microstrip. The microstrip is terminated with a lossy Au meander which thermalizes the radiation. Right: The 150 GHz detectors are fabricated as hexagonal arrays of 84 pixels.

Fig. 6. The 150 GHz arrays shown in fig. 5 will couple to the telescope through a corrugated feedhorn array (left). This array is assembled from a stack of metalized micromachined Si platelets (right).

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Fig. 7. Diagram of the SPTpol focal plane. The central portion of the focal plane will consist of 588 pixels observing at 150 GHz made at NIST. The outer perimeter of the focal plane will be composed of 188 pixels of ANL detectors observing at 90 GHz.


