BOLOMETERIC DETECTOR ARRAYS FOR CMB POLARIMETRY

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ABSTRACT

We describe the development of antenna-coupled bolometers for CMB polarization experiments. The necessary components of a bolometric CMB polarimeter—a beam forming element, a band defining filter, and detectors — are all fabricated on a silicon chip with photolithography. This highly integrated design allows mass production of millimeter wave polarimeters. The readout of thousands of bolometers is done by SQUID multiplexers. We have successfully fabricated and tested several prototype devices. We find their spectral and angular responses in good agreement with the theoretical expectations. The devices are undergoing optimization for future CMB experiments, such as SPIDER and CMBPOL.

INTRODUCTION

The primary science goals of the next generation Cosmic Microwave Background (CMB) polarization experiments are to produce a high fidelity E-mode power spectrum and to search for the primordial gravity waves through B-mode polarization. To achieve these goals in the presence of astronomical foregrounds, the instruments will require a wide frequency coverage, many sensitive microwave detectors, and exquisite control of systematics. Bolometers can provide photon noise limited sensitivity over a wide frequency range. However, the existing semiconductor bolometers (NTD) face difficulties in scaling to kilo-pixel instruments. First of all, NTD bolometers have high impedances ($> M\Omega$). The read-out of these devices involves JFET, whose noise contributions are prohibitively large for multiplexing. The beam collimation is usually achieved with metallic feedhorns, which are too heavy and expensive for thousand pixel arrays. Furthermore, at frequencies lower than ~ 75 GHz, absorber-coupled bolometers with low G (thermal conductance) become mechanically too weak.

We are developing a CMB polarimeter based on antenna-coupled transition edge sensors (TES) that can avoid all these difficulties. In this design, the beam forming slot-antenna array, microstrip band defining filter, and TES detectors are all fabricated on a silicon chip using photolithography. The ease in fabrication allows the implementation of thousands of pixels. The migration from semiconductor bolometers to TES bolometers enables the readout of many pixels with moderate electronics complexity. This is achieved by the superconducting quantum interference device (SQUID) multiplexers. The existing time division multiplexers can read out 32 TES detectors sequentially with little noise degradation [1]. The next generation microwave SQUID multiplexers integrated with HEMT amplifiers will be capable of multiplexing thousands of detectors through a single coaxial cable[2].

In the microstrip-coupling design, only the mechanically robust slot antennas scale with the wavelength. As a result, the entire frequency range of interests in CMB science (~ 30 GHz to 300 GHz) can be covered by a single technology. This microstrip-coupling scheme also allows the signal to be processed *coherently* before being detected as power. We have designed a broad-band 180° hybrid to facilitate simultaneous measurements of Stokes' Q and U parameters. The rapid modulation of polarization can be achieved with on-chip switches. We have developed a polarization switch based on SIS junctions and have obtained some preliminary results.

In the following section, we describe the components of an antenna-coupled TES bolometers and the performance of several prototype devices.

THE BUILDING BLOCKS OF A POLARIZATION DETECTOR

The antennas - In antenna-coupled detectors, traditional metallic feedhorns are replaced by planar antennas consisting of arrays of sub-slots. The signals collected by the sub-antennas are combined coherently by the binary summing trees to form a collimated beam. The planar array design requires no hand-assembly. It also minimizes cross-polar responses and simplifies anti-reflection coating.

The first antenna we developed is a broad-band single polarization long-slot antenna described in [3]. Subsequently we have designed two types of dual-polarization antennas. A trade-off in slot length and periodicity limits the bandwidth of the first dual-polarization antenna to 20%. In the later design, the slots are oriented at 45° with respect to the grid pattern, allowing a bandwidth of 30%.

We have fabricated several prototype antenna-coupled TES bolometers to study their optical responses. The beam maps of a single polarization antenna (Device 1) and a first generation (with a narrower bandwidth) dual polarization antenna (Device 2) are measured with an optically modulated thermal source. The measured FWHM of the two antennas are $\sim 12^\circ$ and 14°, respectively, in agreement with the theoretical calculations (Fig. 1, left panels).

The microstrip filters - Microstrip in-line filters can be integrated with the antenna-coupled detectors, eliminating the need for external metal mesh edge filters used in current CMB experiments. We have developed a lumped-element bandpass Chebyshev LC filter. This filter design is very compact, and is fully compatible with photolithographic processes. The band-gap frequency of the niobium microstrips (~700 GHz) also provides a natural high frequency cutoff for CMB experiments.

The spectral responses of two prototype devices are measured with a Fourier transform spectrometer. A low pass metal mesh filter with a cut-off frequency of 280 GHz is inserted in the optical train for this initial testing. Since the antenna of Device 1 has a bandwidth $> 50\%$, the overall band is defined by the microstrip filter. The spectrum indicates a 35% bandwidth, centered around 120 GHz, 20% higher than the designed frequency. Device 2 has the same microstrip filter, however the bandwidth of its dual polarization slot antennas is intrinsically narrower and centered at 100 GHz. The relative shift in the filter band and antenna band limits its overall bandwidth to $\sim 15\%$. In both devices, the microstrip filters show high out-of-band rejections, and sharp cut-off edges. The two filters on the dual-polarization device show excellent repeatability. Because of their non-resonant nature, these filters are not expected to have harmonic leaks. The spectra for the two devices are shown in Figure 1 (right panels).

The TES bolometers - After the bandpass filter, the signal collected by the antenna eventually dissipates in a meandering resistive microstrip on a SiN leg-isolated island, heating up a TES film. We choose a leg-isolated bolometer over a hot electron bolometer, because it is very straightforward to deliver power into the detector and to control its thermal conductance (G) in the former approach.

Titanium (Ti) has an appropriate superconducting transition temperature ($T_c \sim 0.42$ K) for sub-orbital CMB experiments. The cooling of Ti TES can be provided by a ^{3}He refrigerator, with a base temperature T_b of 0.25 K. For a low background space-borne mission such as CMBPOL, additional gain in sensitivity can be obtained by lowering T_c and T_b. Potential TES materials with T_c lower than 0.2 K are Iridium, Halfnium, and superconductor-normal metal bilayers. In a bilayer TES, the proximity effect in superconductivity allows its T_c to be tailored by varying the thicknesses of two layers. We have fabricated a low G, 8-element Mo/Au bilayer TES array ($T_c \sim 0.12$ K), and have successfully integrated it with the NIST SQUID multiplexing readout. The measured time constants and noise equivalent power ($NEP \sim 2 \times 10^{-18} W/\sqrt{Hz}$) meet the requirements of CMBPOL.

The cooling of the CMBPOL detectors can be provided by a space qualified dilution fridge or an ADR, both of which are in a mature phase. Another possibility is to use the NIS on-chip coolers [4]. An array of these devices can be fabricated on a cooling wafer, on which the antenna-coupled TES wafer is mounted. Starting from the 0.28 K base temperature provided by a ^{3}He fridge, an operation temperature < 0.1 K can be achieved with very little system modification.

The 180° hybrids/polarization modulators - A planar "rat-race" hybrid can be used to introduce 180° phase-shift and mix the signals from each of the polarizations. Using global parameter optimization, we have designed a 180° hybrid that minimizes the polarization artifacts ($< 1\%$) over a 35% frequency range. This element can be used with a power splitter to enable simultaneous $Q - U$ measurements with 4 bolometers for each sky pixel. In the photon shot noise dominated case (Poisson limit), there is no sensitivity gain by adding a factor of two more detectors, because the extra detectors merely compensate the sensitivity degradation. It is nonetheless advantageous for systematics control. On the other hand, at frequencies lower than 90 GHz, where the Bose photon noise starts to dominate, simultaneous $Q - U$ detections do improve the mapping speed by a factor of 2 (if the phonon noise is subdominant).

The microwave impedance of an SIS tunnel junction depends on the supercurrent flowing through it. This property can be used to build a non-dissipative, cryogenically robust switch to control the flow of signals on the

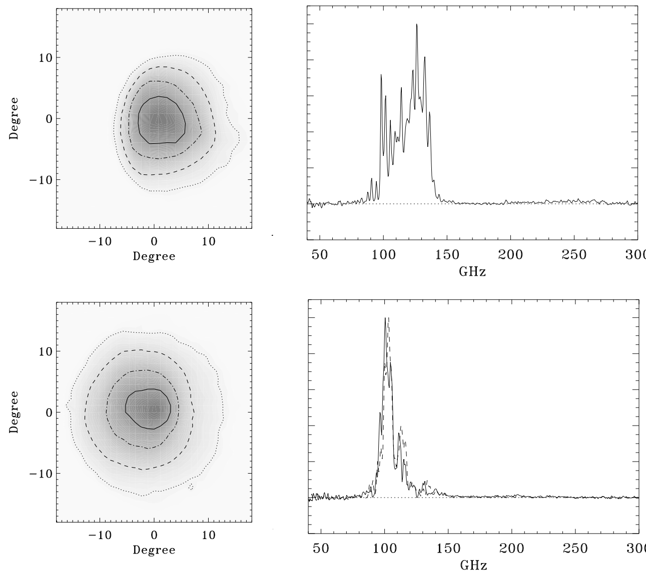

Figure 1: Angular and spectral responses of two antenna-coupled TES bolometers. The contour levels are 75%, 50%, 25%, and 10% of the peak responses. *Top:* The single polarization antenna. *Bottom:* The dual polarization antenna.

microstrips. We have designed a 4-port switching hybrid to modulate the polarizations, aiding measurements of small signals with the standard synchronous detection techniques. The design involves 2 back-to-back quadrature hybrids, with their joining points capacitively coupled to the ground plane through SIS junction switches. Depending on the impedance states of the switches, each of the two output ports is connected to either one of the two inputs. Appropriate combinations of 180° hybrids and polarization switches can be used to achieve rapid modulations between $+U \leftrightarrow -U$ or $+Q \leftrightarrow -Q$.

We have fabricated and tested several prototype polarization switches (Fig. 2, *Left*). The microwave signal is injected into one of the two input ports through a dipole slot antenna. Three detector junctions are used to measure the microwave signals: the first monitors the input power as the reference, and the others monitor the two output ports. The modulation efficiencies are shown in the right panel of Figure (2). The S-parameters are clearly responding to the bias current through the switch junctions. This particular switch shows a 60-90% modulation efficiency in the frequency range of 105 to 115 GHz.

DISCUSSION AND FUTURE WORK

We have experimentally demonstrated the planar antenna-coupled TES concept. This architecture requires no hand-assembly and can be easily scaled to kilo-pixel arrays. Despite the overall agreement with the theoretical models, the optical properties of the prototype detectors require further investigation. The measured beams show some minor asymmetries, which might be due to reflections in the setup and can be reduced by anti-reflection coating the optical elements. The first spectra indicate that the frequency of the filter band is higher than the designed value by approximately 20%. This is likely caused by a variation in the dielectric constant or thickness and can be easily adjusted.

In all the current antenna designs, the sub-antennas are arranged in a square grid pattern, and are excited equally by the feed network. Consequently, the beam response tends to have a four-fold symmetry instead of a circular symmetry. It is straightforward to improve the symmetry and to reduce the sidelobes by redesigning the feed network to "taper" the feed pattern. Alternatively, an optical element that gradually reduces the illumination can be placed at the cold stop, at the expense of a moderate increase in the detector loading.

The initial results from the polarization switches are encouraging. However, they show narrower bandwidth and lower modulation efficiency compared with the designed specifications. This might be caused by disagreements between the designed parameters (critical current density and dielectric constant) and the true values.

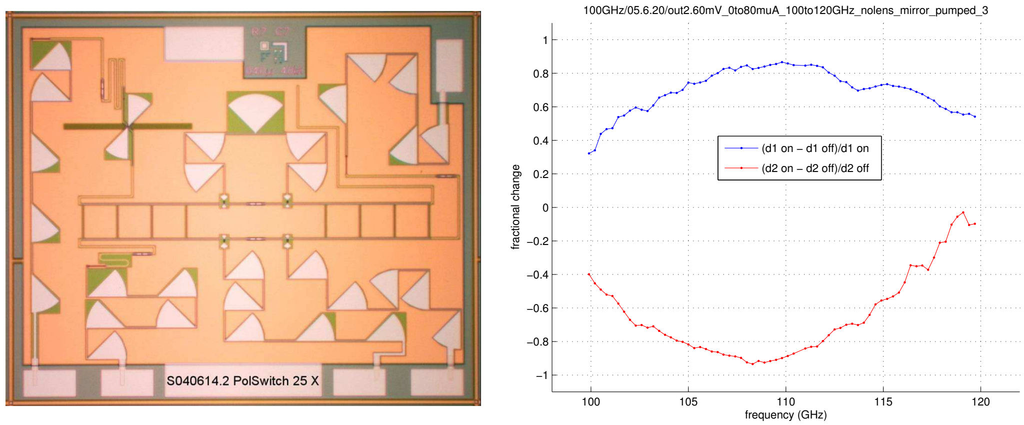

Figure 2: *Left:* The picture of a prototype polarization switch. *Right:* Initial test results from the first switch. The modulation efficiencies for the two output detectors, defined as the difference in the detected signal in the ON and OFF states divided by the signal in the ON state, are plotted as a function of frequency. More than 75% of modulation is achieved over a frequency range of 10%.

A 95% modulation over a bandwidth of 30% can be achieved if the switches are properly tuned.

As a parallel effort, we have started the fabrication of antenna-coupled TES in array formats. The first array has 64 spatial pixels, each with 4 TES bolometers. Each spatial pixel measures Stoke's Q and U simultaneously through the 180° hybrids. A SQUID multiplexing system is being set up for an adiabatic demagnetization refrigerator system to test these arrays. We will first carry out "dark" tests, such as noise characterization, uniformity of TES resistance and transition temperature, magnetic shielding, detector loading, and other system-level issues. Individual pixels from the array will be tested in the ^{3}He optical test-bed.

These antenna-coupled TES arrays are very promising detectors for CMBPOL. A more imminent application is SPIDER, a proposed balloon-borne polarization experiment targeting the B-mode re-ionization bump at $\ell \sim 6$. SPIDER will cover 40% of the sky from a spinning balloon platform. It consists of 6 monochromatic refractive telescopes, each with a 20 cm aperture. This compact design offers excellent optical performance, offering large throughput for a total of 1856 TES bolometers. Since the SIS switch still requires further optimization, the polarization modulation of SPIDER will be achieved with rotating half-wave plates. Once the antenna and filter design are verified at 100 GHz and 150 GHz, prototype devices will be fabricated and characterized for SPIDER's full frequency bands (40 - 220 GHz). Systematic effects, such as side-lobes, beam asymmetries, cross-polarization responses, are under study.

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