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# Antenna-coupled bolometer arrays for measurement of the Cosmic Microwave Background polarization

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**Abstract** We are building antenna-coupled Transition Edge Sensor bolometer arrays to measure the polarization of the cosmic microwave background. 217 GHz prototype pixels have previously been characterized and showed promising performance[1]. Our design uses a double slot dipole antenna and an integrated microstrip band defining filter. New devices have been tested which include on-chip test structures to improve our understanding of detector performance and guide future development. In parallel with this, large arrays of bolometers based on the prototype pixel design have also been constructed. The array pixels are a heterogeneous mixture of single band pixels at 90 GHz, 150 GHz, and 220 GHz and now incorporate dual-polarization antennas[2]. Preliminary results from optical testing of array pixels are presented. These bolometer arrays will be used in the upcoming CMB polarization experiment POLARBEAR .

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## 1 Introduction

In the last several years, measurements of the Cosmic Microwave Background (CMB) temperature anisotropies have helped usher in the era of precision cosmology[3]. The CMB polarization anisotropies also hold enticing information about the nature of the universe[4], however these signals are $10^2 - 10^3$ times fainter than the temperature anisotropies and substantial gains in experimental sensitivities are

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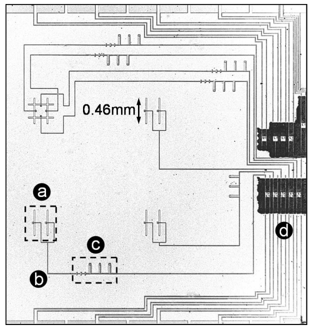


**Fig. 1** Photo of antenna-coupled bolometer prototype chip. (a) Double slot dipole antenna (b) Nb microstrip (c) Microstrip band defining filters (d) TES bolometers. Three of these antennas feed different microstrip filter configurations, while the fourth (upper left) is a dual polarized pixel. On these prototype chips, the dual polarized antennas were not tested as the additional layers needed to fabricate the microstrip crossover were not included.

needed. As single detectors are often photon noise limited in these applications, large detector arrays are critical to meet the needs of future experiments.

Bolometers are the most sensitive broadband detectors of millimeter wavelength radiation and have been used successfully in CMB experiments. The standard lithographic fabrication and multiplexed readout[5] of TES bolometers facilitate the construction and instrumentation of large bolometer arrays. Antenna-coupled bolometers provide a highly integrated detector architecture that further aids large array implementation. Rather than the conventional horn, antenna-coupled bolometers use planar antennas on the detector chip to couple light into the bolometers and define the detector beams. The inherent antenna polarization sensitivity and on-chip transmission line filters take the place of external band defining filters and polarizers. Finally, antenna-coupled bolometers hold the promise of multiband pixels, in which one antenna feeds multiple band defining filters at different frequencies, each of which is then connected to a separate bolometer[6]. In principle, this approach makes the most efficient use of focal plane area.

## 2 Prototype antenna-coupled bolometer pixels

We have fabricated and tested single band antenna-coupled bolometer pixels[1]. These devices use a double-slot dipole antenna in conjunction with a contacting dielectric lens. This combination has been shown to provide highly efficient optical coupling to a telescope, a symmetric beam and good polarization properties[7]. The antenna is fed with superconducting Nb microstrip with a $SiO_2$ dielectric. An integrated $\frac{\lambda}{4}$ shorted stub microstrip bandpass filter is centered at 217 GHz with a 40% bandwidth. The microstrip is terminated with a load resistor on a silicon nitride leg-isolated bridge, which provides the necessary thermal isolation. The power dissipated in the load resistor is then measured by an Al/Ti bilayer TES with a Tc of ~450 mK.

The prototype device performance was encouraging, with a well defined passband and an overall peak receiver efficiency of 20%. The efficiency was substan-

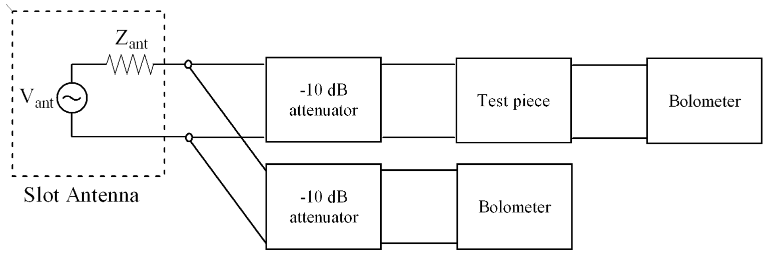


**Fig. 2** Schematic of on-chip transmission test structure. The single antenna feeds multiple bolometer channels, one of which has an inline test piece. This can be any arbitrary 2-port device. Measurement of the spectral response of both channels and calculation of the ratio provides a transmission measurement of the test piece. Lossy microstrips act as attenuators, providing channel isolation and ensuring impedance matching.

tially limited by reflections from the Si lens and by a known mismatch in the load resistor due to a fabrication issue. With an antireflection coated lens and the proper termination resistance, the expected receiver efficiency would be $\sim$40%.

## 3 On-chip test structures

We are using on-chip test structures to improve our understanding of the bolometer elements and to optimize detector performance. One test structure we have developed produces a calibrated transmission measurement of a two port microstrip circuit. A single antenna connects to a power divider, which feeds multiple microstrip channels. Lossy-microstrip attenuators provide isolation between channels. One channel includes the test piece while another channel does not. The power transmitted through each channel is measured in separate bolometers and the ratio of the measured powers is the test piece transmission. This technique strongly rejects off-chip frequency dependent effects, such as fringing in optical elements. It is also insensitive to the properties of the antenna, provided sufficient signal is available for the measurement. These structures are tested using a Fourier Transform Spectrometer (FTS), a standard technique for measuring the spectral response of bolometers. The resulting measurement is similar to a network analyzer transmission measurement, but without the associated difficulty and expense of a 200 GHz network analyzer and cryogenic probe apparatus. The power divider can be designed to feed many test channels at once, ultimately limited by the effects of lower signal per channel. Current test chips use a 4-way power divider, feeding three test pieces and one calibration channel.

Measurements of some of these transmission test structures have been completed. An initial test comparing 4 identical channels indicated that the attenuators are matched to 8% from 150 GHz to 270 GHz. The achievable level of matching is one of the practical limitations of this technique. A transmission test of a 6 mm microstrip line provided a microstrip loss measurement. The observed loss over this frequency range is consistent with an $SiO_2$ loss tangent of $0.005 \pm 0.001$. Figure 3 shows a transmission measurement of a bandpass filter with reasonable agreement in both in-band efficiency and the location of the band edges.

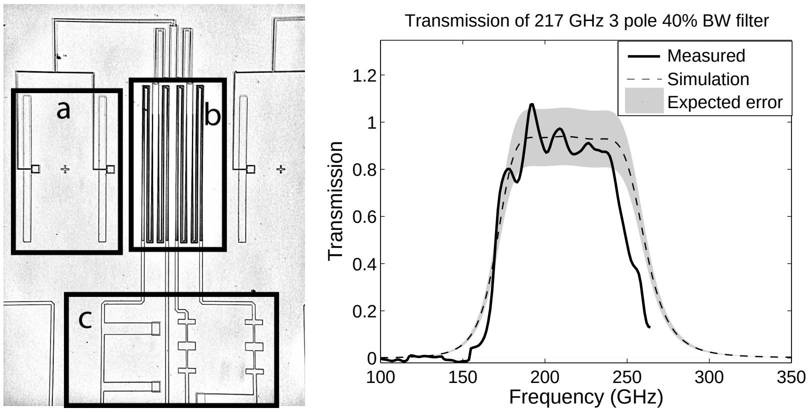


**Fig. 3** Left: Photo of a 4-way transmission test structure: (a) double slot dipole antenna (b) lossy-microstrip attenuators (c) 4 channels with 3 test pieces and one through line channel for calibration. The powers transmitted through the 4 channels are measured by 4 separate TES bolometers (not shown). Right: Measured transmission of 3 pole 217 GHz bandpass filter design from the prototype pixels. Simulation[8] includes the measured 0.005 dielectric loss tangent. Shaded region is expected error due to attenuator mismatch alone. High frequency cutoff in data is due to low signal to noise as the attenuation rises with frequency.

Similar test structures are being developed for inclusion in unused regions of bolometer array wafers. They will serve as a process monitor during ongoing production.

## 4 Antenna-coupled bolometer arrays for POLARBEAR

The POLARBEAR focal plane is 14 cm in diameter, populated with 180 dual-polarization antenna-coupled bolometer pixels (360 bolometers) in a four fold symmetric arrangement achieved on four standard 4" silicon wafers. Several versions of these arrays have been fabricated, with the recent incarnation providing pixels with promising microwave properties. The POLARBEAR optical test cryostat, a large field of view liquid cryogen dewar commissioned for testing of the POLARBEAR detector arrays, was used to test witness pixels from the array wafer. The preliminary results from these tests are included below.

The on-axis polarization response of the antenna was tested through an aperture 6 degrees in diameter. A thin-film wire-grid polarizer on a calibrated rotating mount was used to polarize modulated radiation transmitting through the aperture. The response of both of the bolometers connected to a 90 GHz dual-polarization pixel was recorded as a function of polarization angle. Figure 4 clearly shows the expected sinusoidal response of each detector to polarizer angle, as well as the 90 degree rotation of the polarizer between the detectors' peak responses.

A Fourier Transform Spectrometer (FTS) was used to characterize the spectral response of the 90 GHz detector discussed above, as well as one polarization of a 150 GHz detector. Data are plotted in Figure 5, along with the design bands, which have been shifted down 3.2% in frequency to better compare design

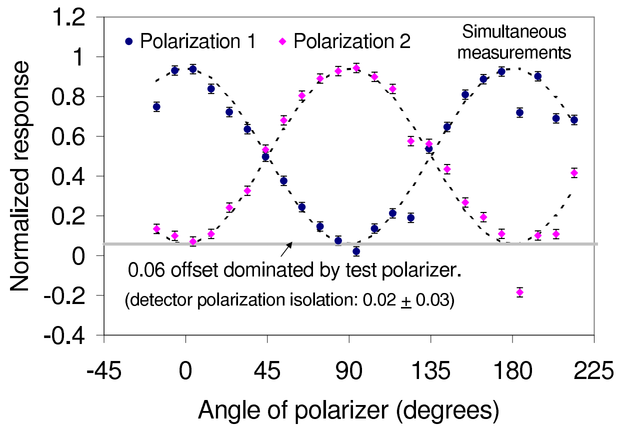


**Fig. 4** First simultaneous measurement of dual-polarization pixel, showing band-averaged on-axis polarization response of each detector. Sine and cosine curves are indicated to guide the eye. Obvious systematic negative offset in some data are due to transient radio frequency interference.

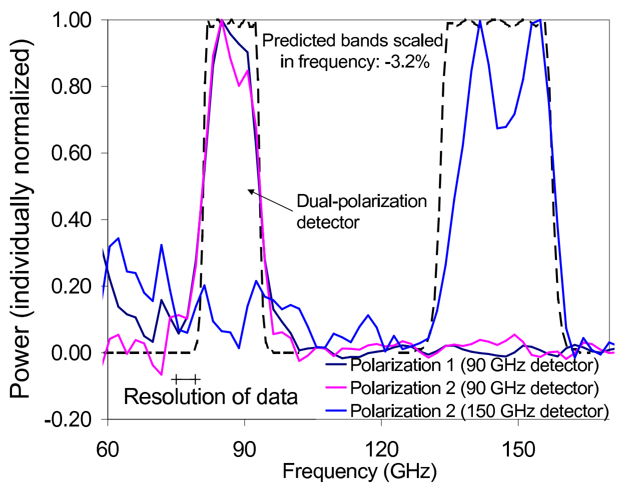


**Fig. 5** Detectors spectral response measured with Fourier Transform Spectrometer (FTS). Signal/noise ratio decreases at lower frequencies because of FTS source power. Note correct bandwidths and bands shifted by only 3.2%. Fringing in 150 GHz band is significant, and requires further study. 220 GHz detector not shown.

and achieved bandwidth. This overall multiplicative shift in the frequency of the bands is within expected fabrication tolerances, possibly due to imperfect control of dielectric thickness. Along with the 220 GHz passband shown in section 1, all frequency bands of the POLARBEAR experiment have been demonstrated.

The passband data for one of the 90 GHz bolometers was used to calculate an expected response to a thermal source, which for $k_B T >> h\nu_{band}$ and unit efficiency through a single-moded antenna is simply $P = \int_{band} k_B T$. Comparing the measured detector response to this calculation provides an overall receiver

| Receiver Element | Estimated efficiency | Estimate uncertainty |
|---|---|---|
| 2” foam window | 0.997 | $\pm$ 0.002 |
| Single-layer low pass filter | 1.0 | - 0.02 |
| Multilayer metal mesh filters (4) | 0.85 | $\pm$ 0.05 |
| Beam truncation by aperture | 0.9 | $\pm$ 0.05 |
| Reflection loss at silicon lens[9] | 0.7 | - 0.03 |
| Antenna frontlobe efficiency[9] | 0.91 | $\pm$ 0.01 |
| Microstrip filter | 0.73 | $\pm$ 0.05 |
| Cumulative receiver efficiency | 0.35 | $\pm$ 0.04 |

**Table 1** Table showing expected transmission efficiency of all receiver elements at 90 GHz, multiplied to derive an expected cumulative receiver efficiency. This compares favorably with the measured $0.32 \pm 0.06$.

efficiency, which for this detector in the POLARBEAR optical test cryostat was $32 \pm 6\%$. The detailed accounting of receiver elements given in Table 1 shows that this promising efficiency is consistent with known losses in the system. Table 1 also indicates where the largest gains in efficiency could be found: the reflection loss in the silicon lens could be reduced substatially with a single $\lambda/4$ anti-reflection coating, and the dielectric loss in the resonant filter can be reduced by adjusting filter design.

## 5 Conclusions

We have demonstrated a viable prototype antenna-coupled bolometer pixel. We have continued to work to better characterize these devices, in part through the use of diagnostic test structures on the detector chips. Dual-polarization, three band antenna-coupled bolometer arrays have been fabricated and preliminary optical tests of witness pixels have been carried out. The passbands are well located and optical efficiency is quite high. Further array fabrication and optical testing should yield high performance detectors for the POLARBEAR experiment.

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