Focal Plane Arrays of Voltage-Biased Superconducting Bolometers

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Introduction

The 200µm to 3mm wavelength range has great astronomical and cosmological significance. Science goals include characterization of the cosmic microwave background, measurement of the Sunyaev-Zel'dovich effect in galaxy clusters, and observations of forming galaxies. Cryogenic bolometers are the most sensitive broadband detectors in this frequency range. Because single bolometer pixels are reaching the photon noise limit for many observations, the development of large arrays will be critical for future science progress.

Voltage-biased superconducting bolometers (VSBs) have several advantages compared to other cryogenic bolometers. Their strong negative electrothermal feedback enhances their linearity, speed, and stability. The large noise margin of the SQUID readout enables multiplexed readout schemes, which are necessary for developing large arrays. In this paper, we discuss the development of a large absorber-coupled array, a frequency-domain SQUID readout multiplexer, and an antenna-coupled VSB design.

Absorber-Coupled Filled VSB Arrays

A closely packed array of bolometers mounted directly in the focal plane of a telescope can give a higher overall efficiency than other designs. We have developed a monolithic design for large format filled arrays of absorber-coupled voltage-biased superconducting bolometers [1].

The thermal isolation required by a bolometer creates a challenge in developing a close packed array. Our design (Figure 1) makes use of a folded leg suspended structure with a square absorber to allow for an array with a high filling factor while maintaining the requisite thermal isolation. The absorber is an open mesh, allowing for efficient absorption of mm-wave optical power while minimizing the cosmic ray cross section. The open mesh absorber was pioneered with "spiderweb" semiconducting bolometers [2] and VSBs in that geometry have been fabricated by our group [3]. However, the spiderweb geometry is not well suited for a close packed array.

Single pixel prototype devices were constructed using standard microfabrication techniques. The low stress silicon nitride was deposited on a

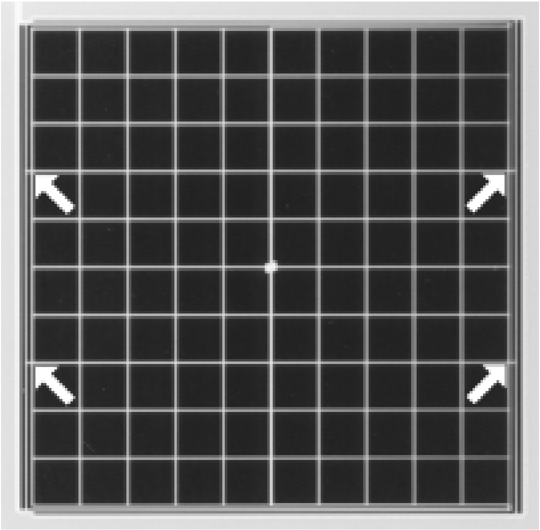

Figure 1 : Prototype single pixel for the filled array design. The absorbing grid is a silicon nitride mesh 1.5 mm on a side. The nitride grid is suspended at four points (arrows) where it is attached to tensioned nitride beams along the left and right sides of the grid. The electrical leads are supported by the nitride beams along the top and bottom of the grid. The leads make contact to the superconducting thermistor on the small patch of nitride at the center of the grid.

standard silicon wafer. The thermistor and leads were then deposited together as four successive layers consisting of Al/Ti/Al/Ti. The thick upper Al layer was etched off the top of the thermistor to create a region with a lower critical temperature (Tc) than the leads around it. Adjusting the thicknesses of the Al and Ti allows the Tc of the thermistor to be controlled. The nitride was then etched into the square mesh pattern using a fluorine plasma etch. A XeF_2 gaseous etch was used to etch the silicon underneath the nitride from the front side of the wafer.

A prototype was tested at a base temperature of 264 mK. The device was voltage biased by current biasing a 20 mΩ shunt resistor and the bolometer current was measured using a SQUID ammeter. The noise spectra were measured with a spectrum analyzer and the noise equivalent power is plotted in Figure 2. The thermal conductance was measured to be $G = 2.7 \times 10^{-11}$ W/K.

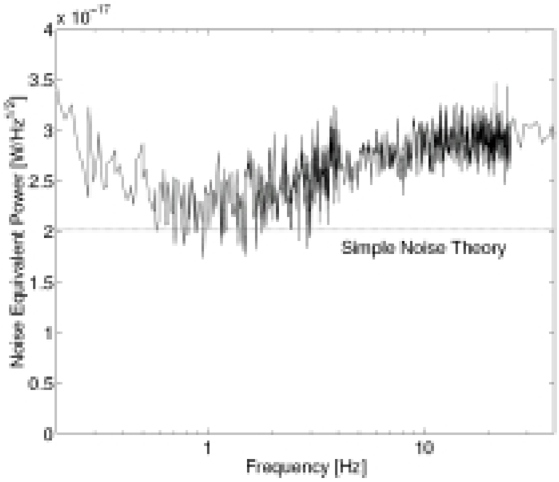

Figure 2 : Measured noise equivalent power for prototype bolometer

To optimize the optical coupling, future devices will have a reflective metal deposited on the back of the wafer as depicted in Figure 3. In free space, the distance between the reflector and the absorber should be ¼ λ to maximize absorption. The presence of silicon over part of the distance modifies the optimal length somewhat. Using SOI wafers and trench etching techniques, the reflector can accurately be placed at the correct distance [4].

In order to test the mechanical stability of this design and its suitability for use in large arrays, several nitride structures were constructed for bolometer arrays ranging from 4 x 4 to 32 x 32 pixels. Pictured in Figure 4 is the nitride mesh structure for a 32 x 32 pixel array. The nitride meshes are spaced to allow 1 µm leads with 1 µm spacing to each pixel. A similarly constructed

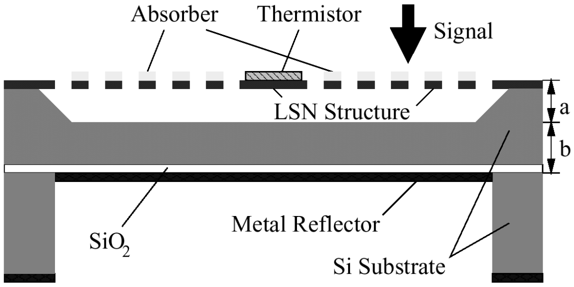

Figure 3 : Cross section of bolometer with the proposed reflector on the back side. The vertical scale has been exaggerated.

bolometer array would give a filling factor of 88%.

All of the elements in the pictured array are intact, but 10 of the 1024 meshes show defects due to dust contamination. The other nitride arrays had a similarly high yield. The devices also proved to be more robust during handling than the previously manufactured spiderweb bolometers [3]. This is likely due to the continuous silicon substrate beneath the nitride suspensions.

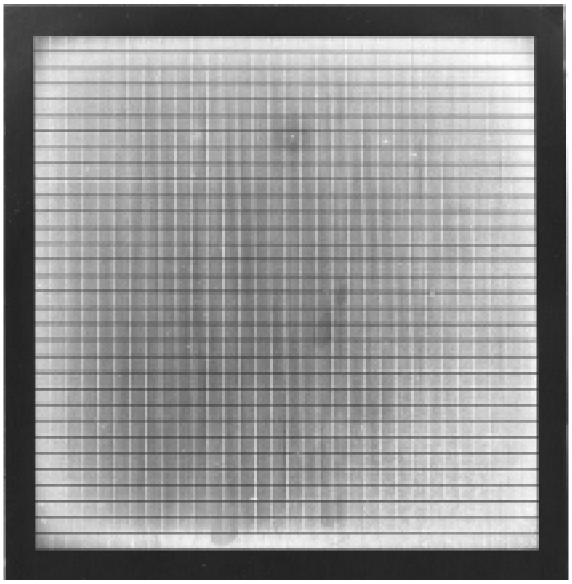

Figure 4 : 32 x 32 array of silicon nitride meshes

Antenna-Coupled VSB Arrays

Using an antenna to couple optical power into a bolometer offers some advantages. The antenna pattern can be used to control the solid angle visible to the bolometer much as a horn does but with much greater scalability. The transmission line typically used to feed the antenna can also incorporate filters, further integrating the required optical components onto the substrate. Planar antennas are also polarization sensitive, which can be quite useful for some experiments. One potential application is the measurement of the polarization of the cosmic microwave background. We are currently developing an antenna coupled bolometer design using planar antennas, transmission line filters, and lithographed VSBs.

Our current design uses a dual slot dipole planar antenna [5]. This antenna is well suited to this application as it has a symmetric beam pattern and provides a good impedance match to microstrip transmission lines. Typically a dielectric lens in direct contact with the antenna is used and the parameters of the lens and antenna can be tuned to provide a good match to the f/# of a telescope. A variant of the dual slot antenna that is sensitive to dual polarizations has been developed by Chattopadhyay and Zmuidzinas [6].

Superconducting niobium microstrip is used to feed the antenna. Superconducting microstrip is very low loss for frequencies well below that corresponding to twice the gap energy of the superconductor. Niobium is in this regime for the frequencies of this design (150-300GHz).

Band defining planar filters will be fabricated in niobium microstrip. There is a considerable amount of knowledge regarding the design of these filters in the literature. After filtering, the transmission line is terminated with a load resistor on a suspended nitride VSB. This places the load in good thermal contact with the superconducting thermistor.

We are currently working to build a prototype antenna-coupled pixel. The highly integrated nature of the design should make it easily scalable to very large arrays. Since the microstrip is low loss, it can be used to route the RF to the perimeter of the antenna array, where there is significant room for the filters, bolometers, and SQUID readout.

Frequency Domain SQUID Multiplexer

Far-infrared to millimeter wave telescopes can accommodate 10^3-10^4 element arrays, but a readout multiplexer will be required to instrument such arrays. The complexity and heat load of the readout limits the number of bolometers in current array receivers to ~10^2. A multiplexer can alleviate these problems by allowing one readout channel to service several pixels, thus reducing the wire count required for a given number of pixels. The SQUID readout of a VSB is well suited to multiplexing schemes due to its low noise and high bandwidth.

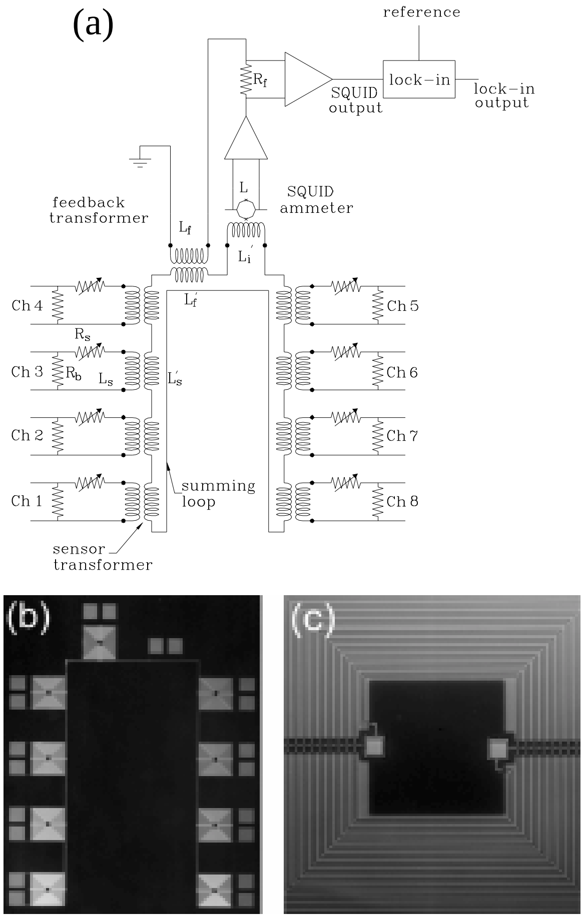

Figure 5 : (a) Schematic of the eight channel multiplexer (b) photograph of the test device (c) close-up of the center of one of the niobium transformers

We have developed a frequency domain single SQUID readout multiplexer suitable for use with superconducting bolometers [7]. A schematic of an 8 channel multiplexer using this design is pictured in Figure 5a. Each bolometer is AC biased at a different frequency and they are then coupled to a superconducting summing loop with a transformer. The current in the loop is measured with a SQUID ammeter. The individual signals are recovered by lock-in detection at the output of the SQUID electronics. The current in the summing loop is nulled by feedback to prevent crosstalk between the detectors.

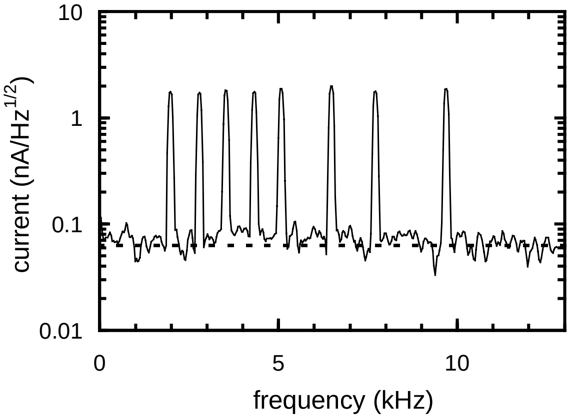

Figure 6 : Spectral density of SQUID output with all 8 channels AC biased

We fabricated an eight channel multiplexer as depicted by the schematic in Figure 5a. Photographs of an actual chip are shown in figure 5b and 5c. The transformers and summing loop are made of thin film niobium. The transformers consist of two intertwined spiral coils over a split niobium washer to maximize magnetic coupling. A SiO_2 insulating layer separates the niobium layers. The summing loop is connected to the SQUID input coil via niobium wirebonds.

The multiplexer was tested at 4.2K, at which temperature the niobium is superconducting. Resistors were used as simulated bolometers and bias was applied at frequencies ranging from ~2–10kHz. The bias frequencies were spaced so as to avoid the overlap of harmonics. The spectral density of the SQUID output can be seen in Figure 6.

In order to simulate an actual bolometer signal, seven of the eight channels were 2% AC modulated at unique low frequencies from 1.6 to 19Hz. The eighth channel was not modulated in order to simulate a no signal condition. The individual signals were recovered by locking in to the bias frequency for the channel of interest. The spectral density of the lock-in output is shown in Figure 7 for one of the channels with a simulated signal (upper trace) and the eighth channel with no simulated signal (lower trace). A crosstalk of < 1% was measured, which may be due to the drive electronics.

Current work on the multiplexer involves a new design, which will operate at significantly higher bias frequencies making it suitable for faster bolometers. We are also working to incorporate filters at the input of each channel in order to prevent the broadband Johnson noise of each detector from affecting the other detectors on the same summing loop.

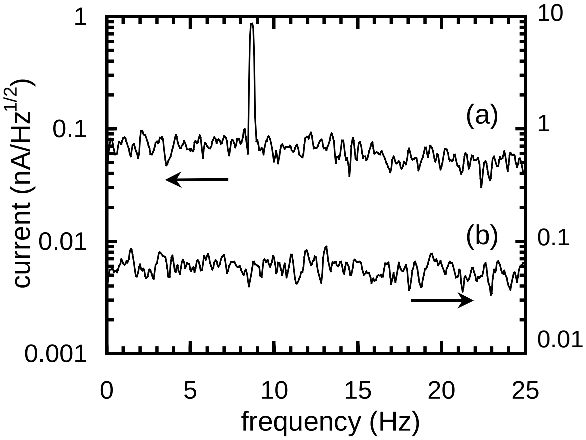

Figure 7 : Spectral density of lock-in detected SQUID output referenced to (a) Channel 5 (simulated signal) and (b) Channel 8 (no signal)

Acknowledgements

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