Recent Advances in Frequency-Multiplexed TES Readout: Vastly Reduced Parasitics and an Increase in Multiplexing Factor with sub-Kelvin SQUIDs

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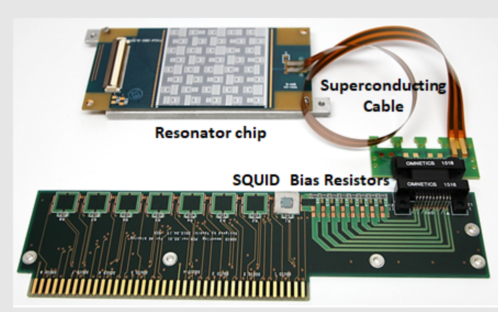
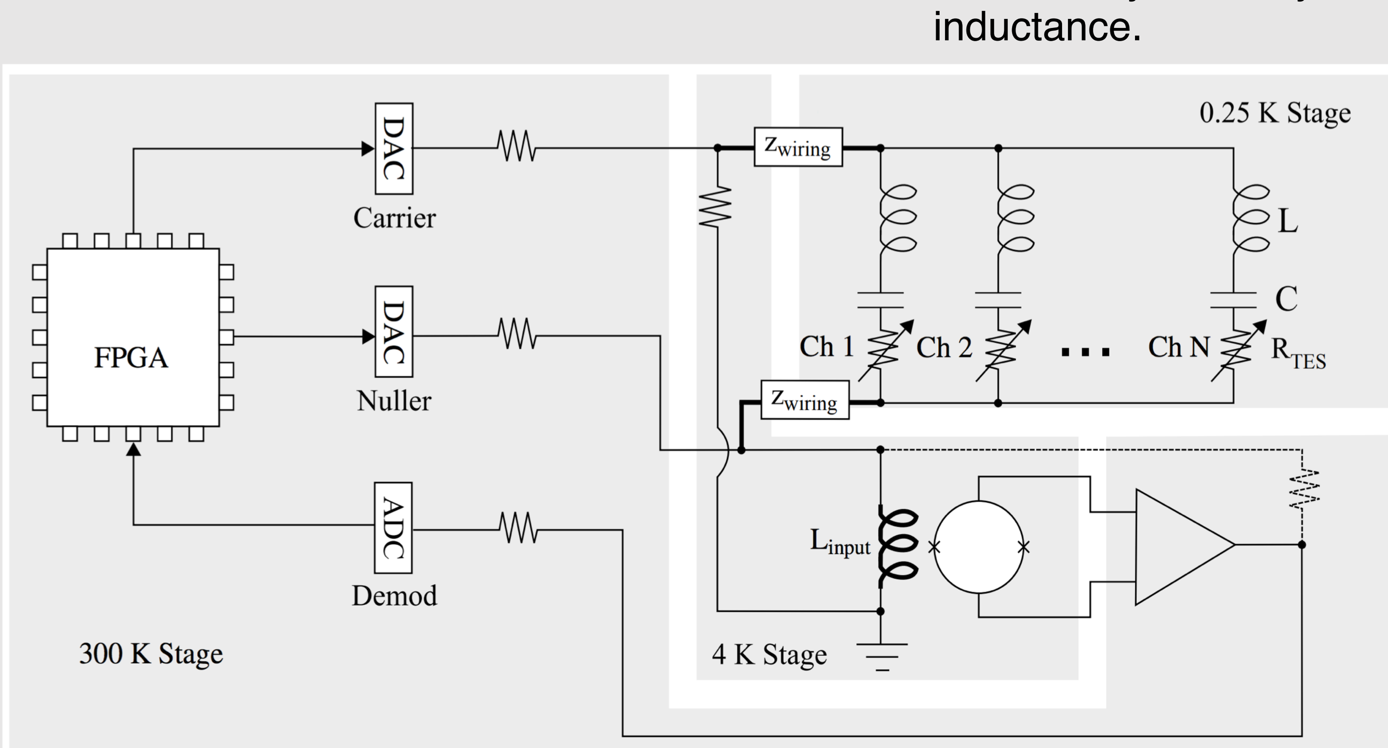
Abstract: Cosmic microwave background (CMB) measurements are fundamentally limited by photon statistics. Therefore, ground-based CMB observatories have been increasing the number of detectors that are simultaneously looking at the sky. Thanks to the advent of monolithically fabricated transition edge sensor (TES) arrays, the number of on-sky detectors has been increasing exponentially for over a decade. The next-generation experiment CMB-S4 will increase this detector count by more than an order of magnitude from the current state-of-the-art to ~500,000.
The readout of such a huge number of exquisitely precise sub-Kelvin sensors is feasible using an existing technology: frequency-domain multiplexing (fMux). To further optimize this system and reduce complexity and cost, we have recently made significant advances including the elimination of 4 K electronics, a massive decrease in parasitic in-series impedances, and a significant increase in multiplexing factor.

Legacy implementation of fMUX: The frequency-domain multiplexing system (fMUX) employs an LC resonator in series with each TES in order to read out multiple detectors over a small number of wires, decreasing thermal load on the cryogenic stages and decreasing cost and complexity of the readout chain.



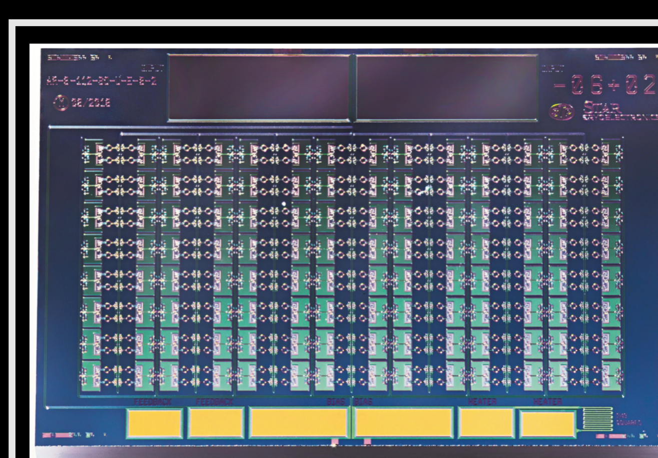
Legacy readout electronics: the broadside coupled NbTi striplines are required to have low thermal conductivity and very low inductance.



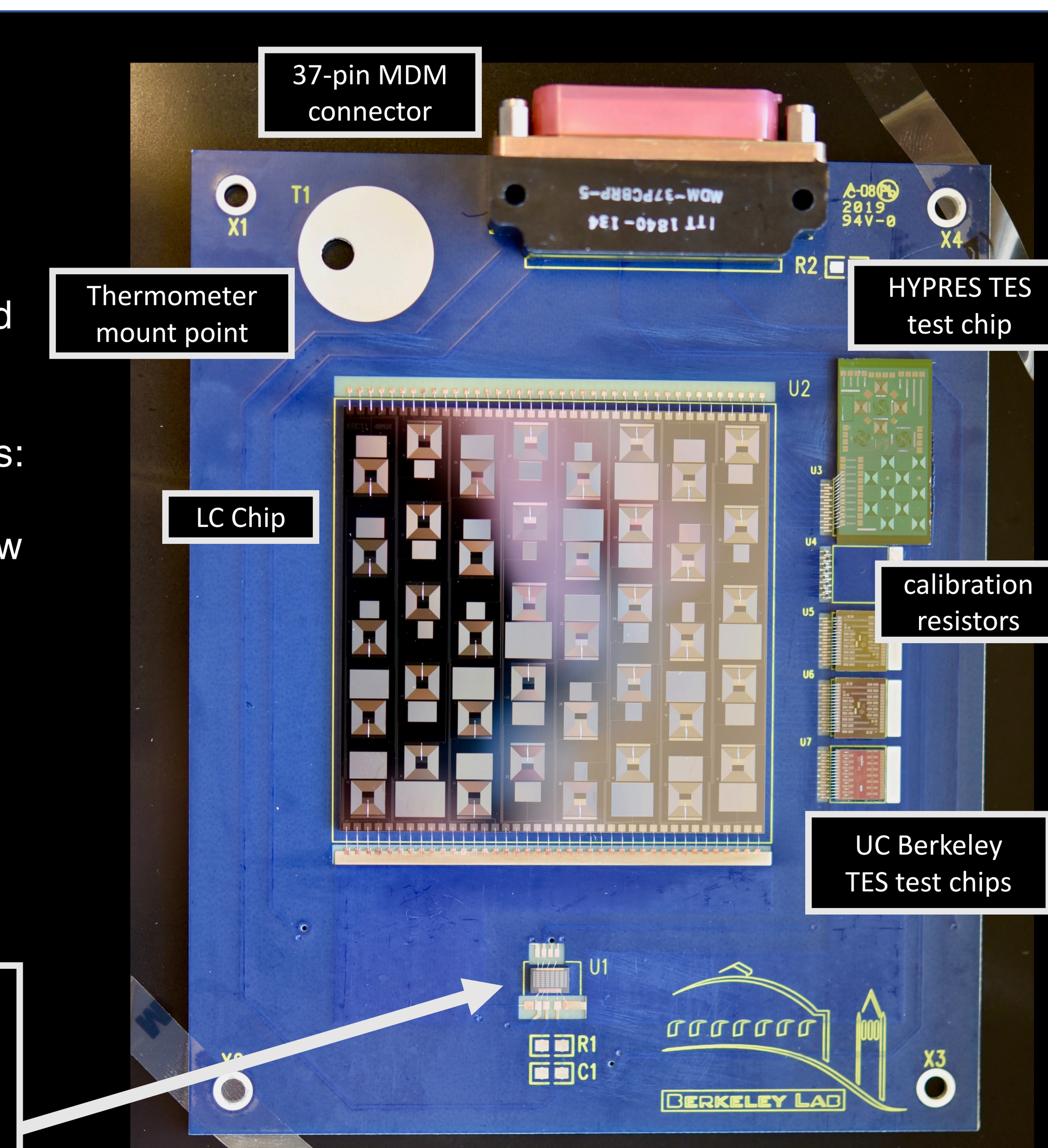
Schematic showing legacy DfMUX readout system. The parasitic inductance z_{wiring} associated with the 250 mK ↔ 4 K wiring is critical to overall system performance.

Implementation of sub-Kelvin SQUIDs and reactive biasing: the advent of low power-dissipation (~10 nW) SQUID amplifiers coupled with a dissipationless bias element allows for the elimination of the 4 K electronics, with several advantages:

- Reduced system complexity
- No need for a low-inductance, low thermal conductivity superconducting stripline
- Vastly reduces parasitic series impedance to the TES
- Improved detector stability, linearity, and crosstalk
- Opportunity to increase multiplexing factor further



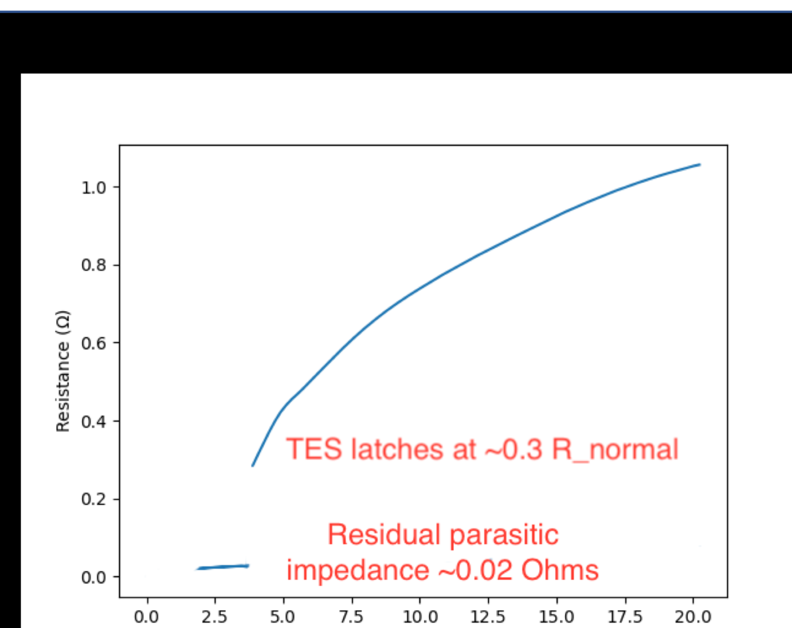
STAR Cryogenics 112-element Series SQUID Array Amplifier



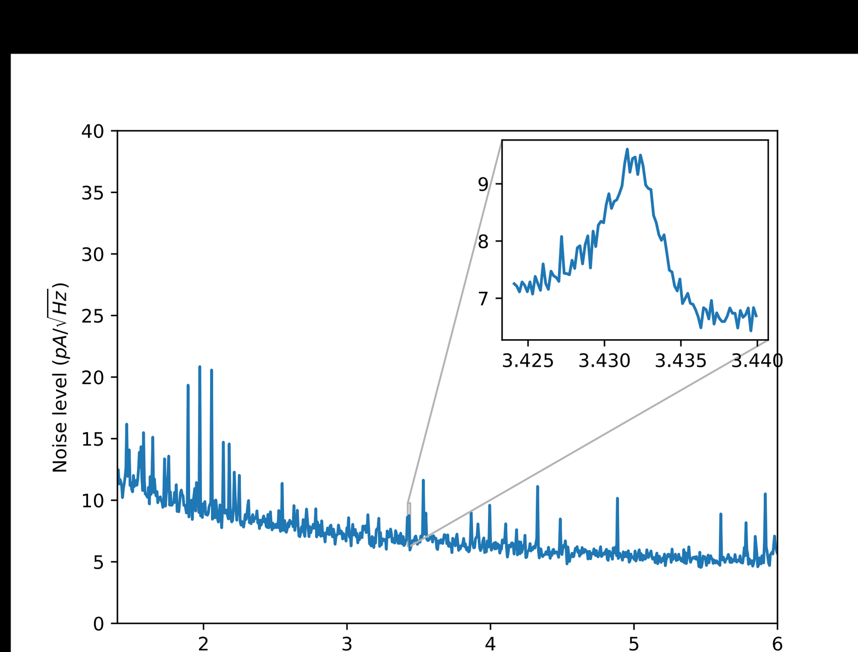
Dark demonstration module with mounted components and wirebonds prior to assembly into mechanical enclosure with magnetic and light-tight shield. The module is used to demonstrate verify readout performance in the presence of sub-Kelvin SQUID operation and a reactive bias circuit.

Results: the 40x demonstration module implementing sub-Kelvin SQUIDs and reactive biasing was used to read out dark TESs. We find that

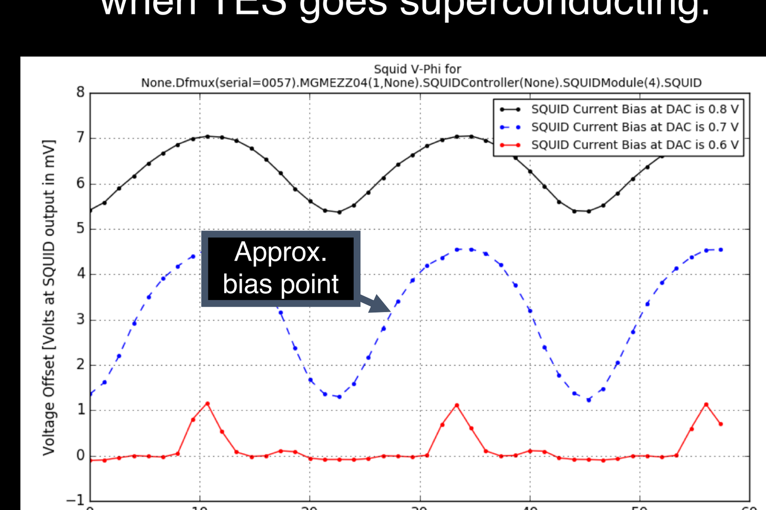
- All 40 sensors show transitions
- When the TES is superconducting, the residual measured impedance is quite low (~0.02 Ω)
- The measured noise level matches rough expectations and is below the requirement



Parasitic impedance reduced to ~10 nH. TES gets deep into transition with strongly reduced measured impedance when TES goes superconducting.

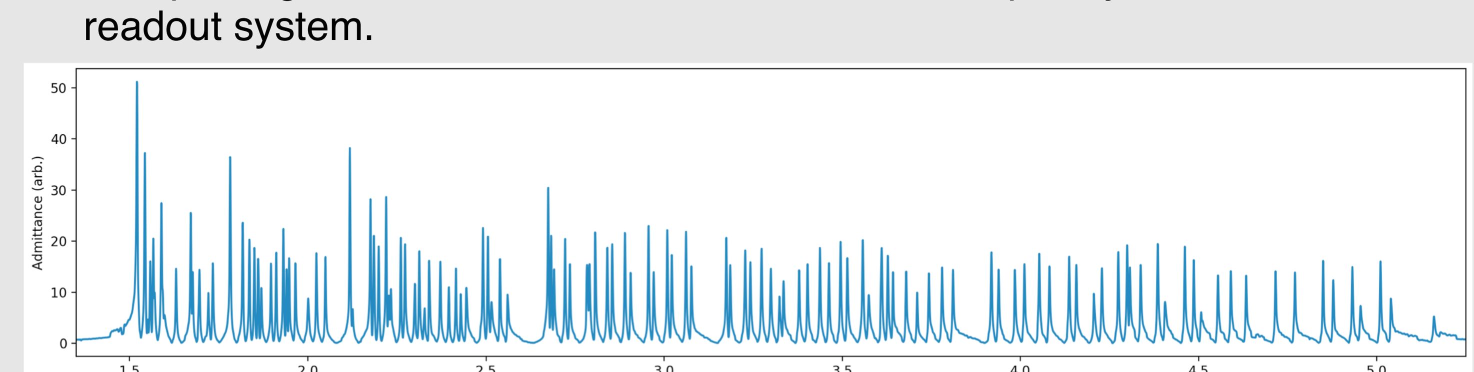


Measured on-resonance and off-resonance matches expectation and requirement of <12 pA/rtHz.

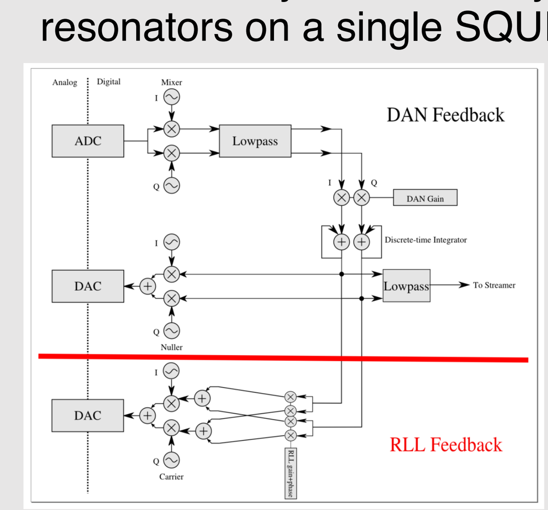


Acceptable SQUID V-Phi curve despite insufficient magnetic shielding in first iteration of the readout module.

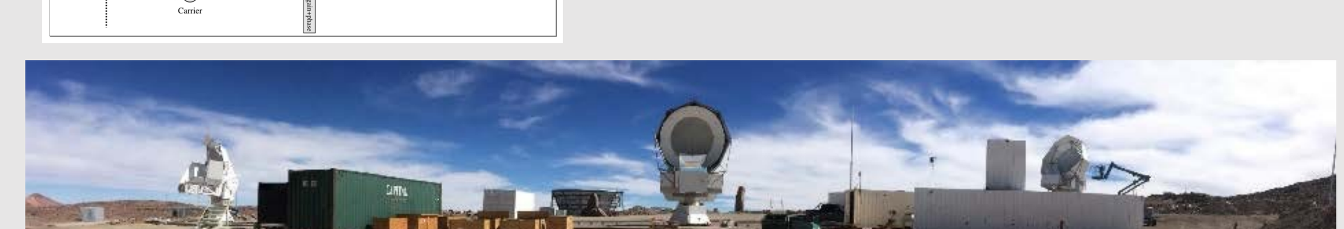
132x multiplexing: Currently deployed iterations of the legacy system use multiplexing factors of up to 68x. By increasing the multiplexing factor, we further reduce cost and complexity of the readout system.



Network analysis of an early test chip implementing 132 LC resonators on a single SQUID channel.



Firmware design of a resistance-locked loop that overrides electrothermal feedback and fixes the operating point of the TES. This drastically improves TES linearity, calibration, and stability. Testing of this firmware implementation will begin soon.



The Simons Array project will implement an on-sky demonstration of fMUX readout with sub-Kelvin SQUIDs and reactive biasing. This is expected to be deployed around the end of 2019 on the PB2c camera.