Frequency Multiplexing Readout for Transition-edge Sensors

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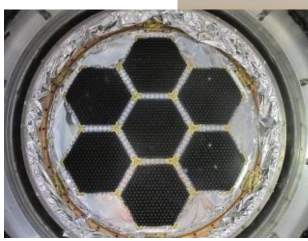
Overview

1. How it works
2. Current implementation
3. Future R&D

Motivation



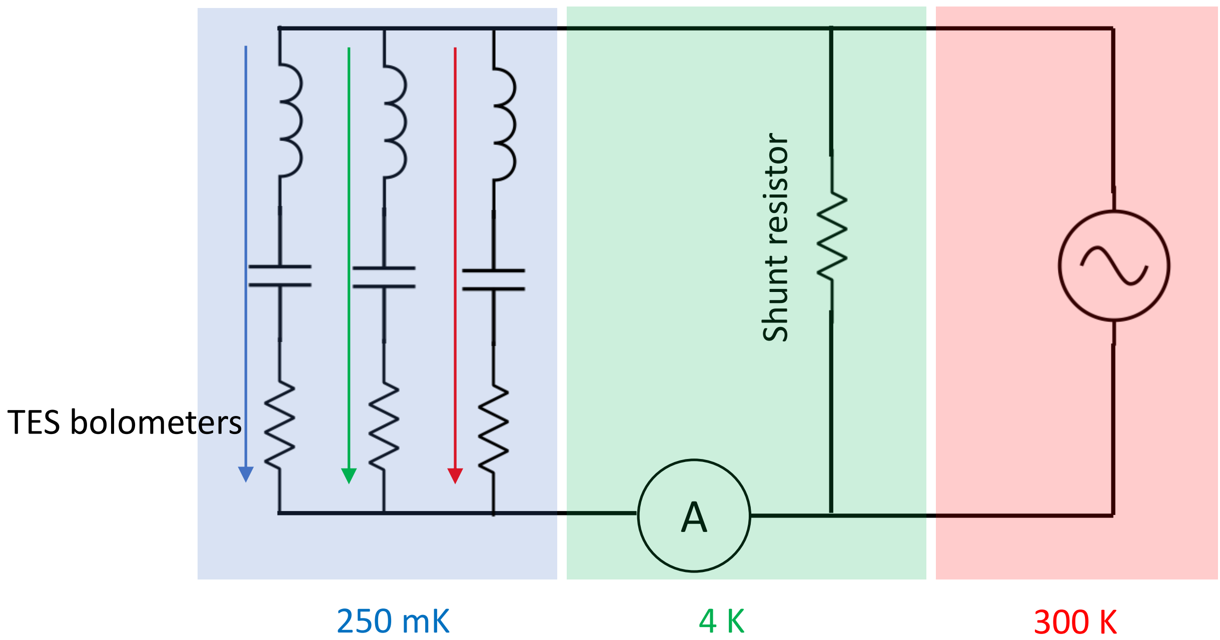
POLARBEAR-2 Focal Plane

SPT-3G Focal Plane

- Current CMB experiments’ detector counts are **~10,000**
- Detectors are at **250 mK**, SQUID amplifiers are at 4 Kelvin

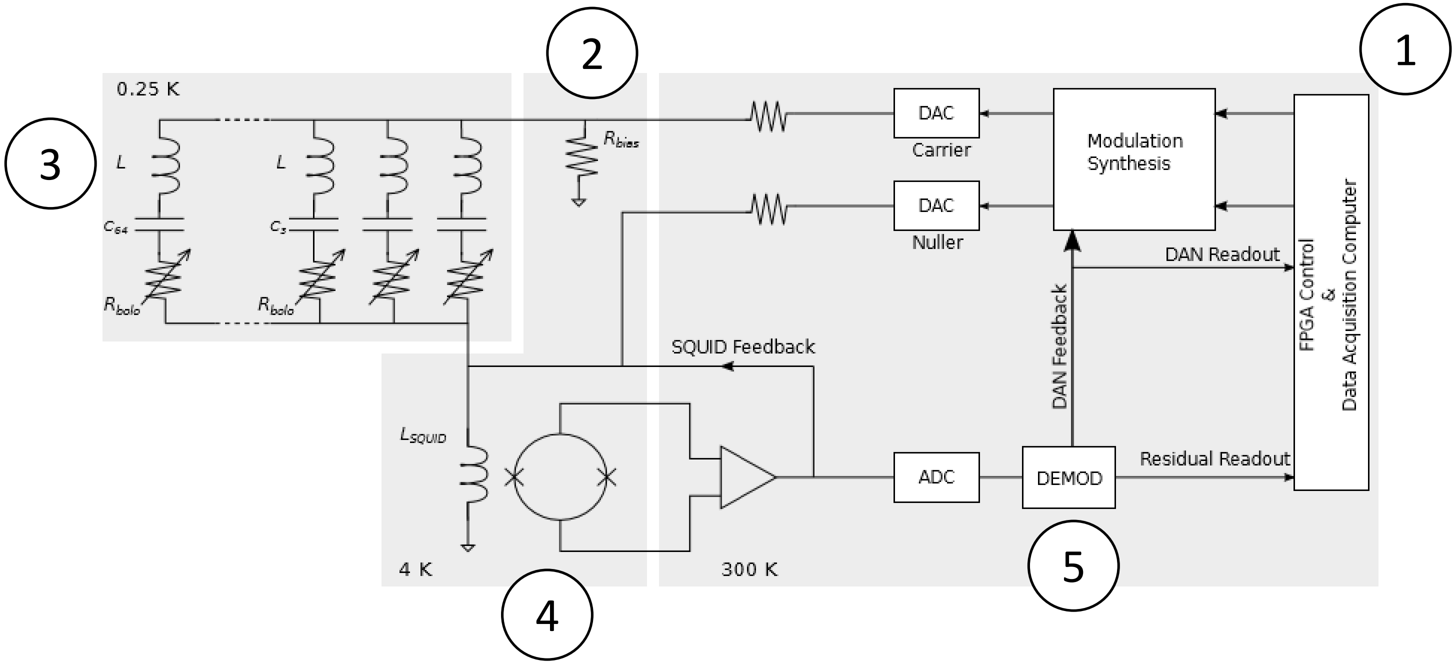
- **Reduce number of wires between 4 K and 250 mK stages**
- **Reduce amount of readout electronics**

Frequency multiplexing: Basic Idea



1. TES is a low impedance device → voltage bias → measure current (A = ammeter)
2. Send in multiple tones. LCR resonators separate frequencies
3. Measure current. Demodulate output for a signal

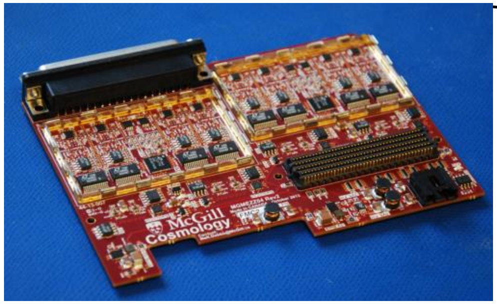
Frequency multiplexing: Operation



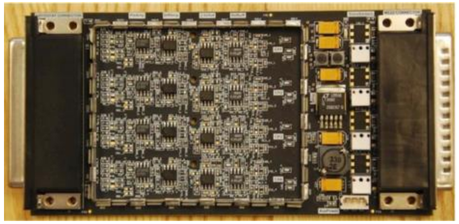
1. Warm electronics synthesizes multiple frequency tones
2. Shunt resistor set voltage bias
3. Superconducting resonators assign frequency to each TES bolometer
4. SQUID and opamps amplifies signal
5. Warm electronics demodulates signal

[1] M. A. Dobbs *et al*., “Frequency multiplexed superconducting quantum interference device readout of large bolometer arrays for cosmic microwave background measurements,” Rev. Sci. Instrum. vol. 83, 073113, (2012).

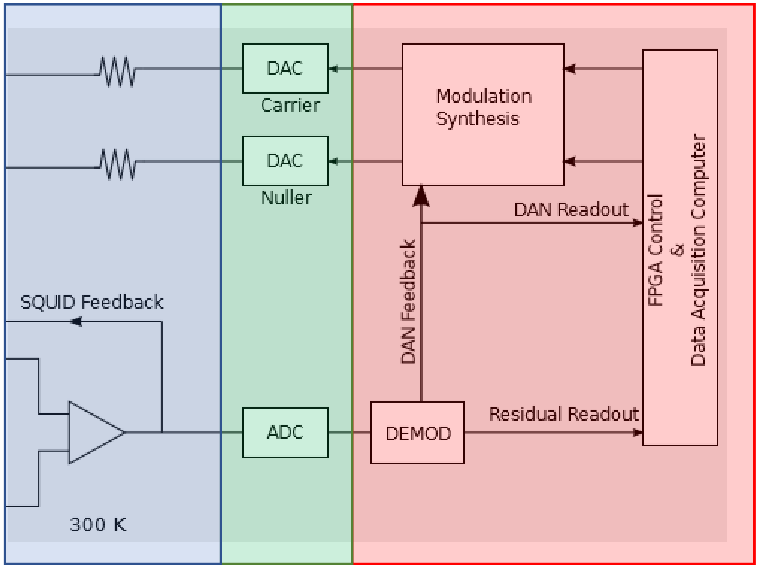
Room Temperature Electronics

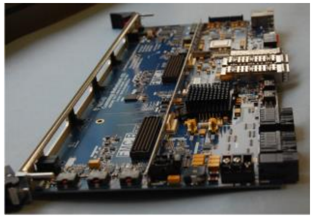


DfMUX mezzanine board



SQUID controller



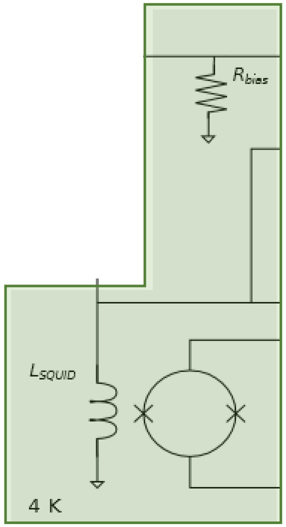


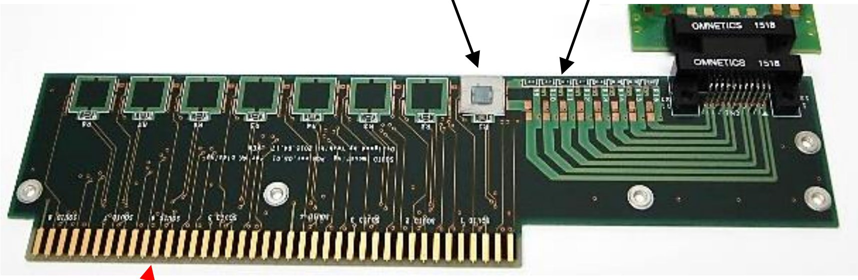
ICE board

[1] K. Bandura et al., ICE: a scalable, low-cost FPGA-based telescope signal processing and networking system J.Astron.Inst. 05 (2017) no.04, 1641005 arXiv:1608.06262

- **ICE board**
  - Xilinx Kintex-7 FPGA
  - 20W ~ 60W power consumption
  - Currently designed to multiplex up to 128 channels
- **DfMUX mezzanine board**
  - Two 16-bit DACs operating at 20 MSPS (50 MSPS available)
  - One 14-bit ADC operating at 20 MSPS (50 MSPS available)
  - Anti-aliasing filter
- **10 MHz SQUID controller**
  - Tunes SQUID, first stage 300 K amplification

4 Kelvin Electronics



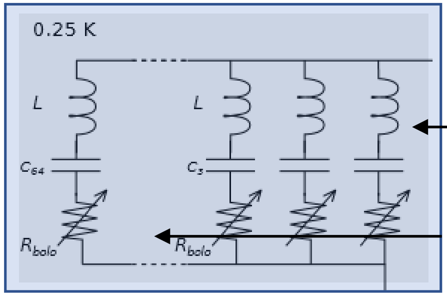


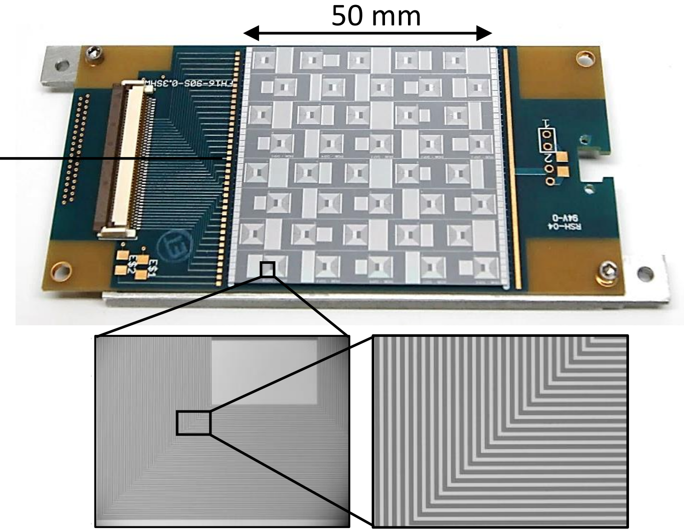
SQUID and bias circuit (4K)

- **Bias circuit**
  - 30 milli-Ohm shunt resistor
- **SQUID**
  - Series SQUID array
  - High transimpedance (500 V/A) and low input inductance (< ~50 nH)
  - **Digital Active Nulling (DAN) feed back system** nulls current flow into the SQUID for nonlinear SQUID operation

[1] Tijmen de Haan *et al.*, "Improved Performance of TES Bolometers using Digital Feedback," Proc. SPIE 8452, 84520E (2012), DOI 10.1117/12.925658.

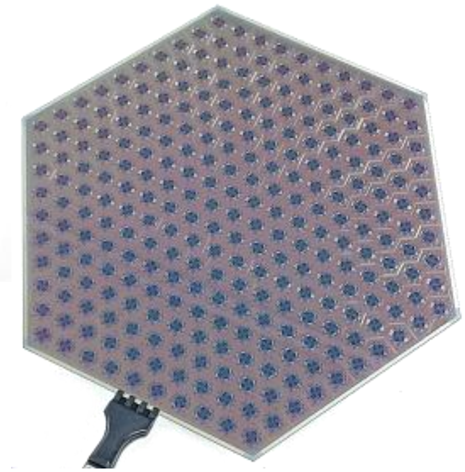
Sub-Kelvin Electronics





4 micron line inductors

LC resonators



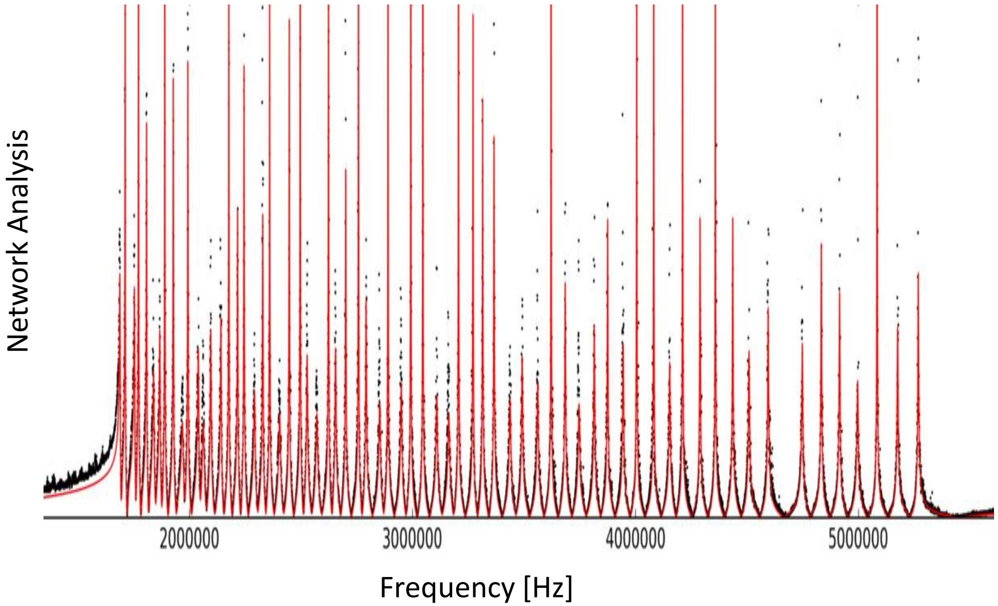
TES detector array

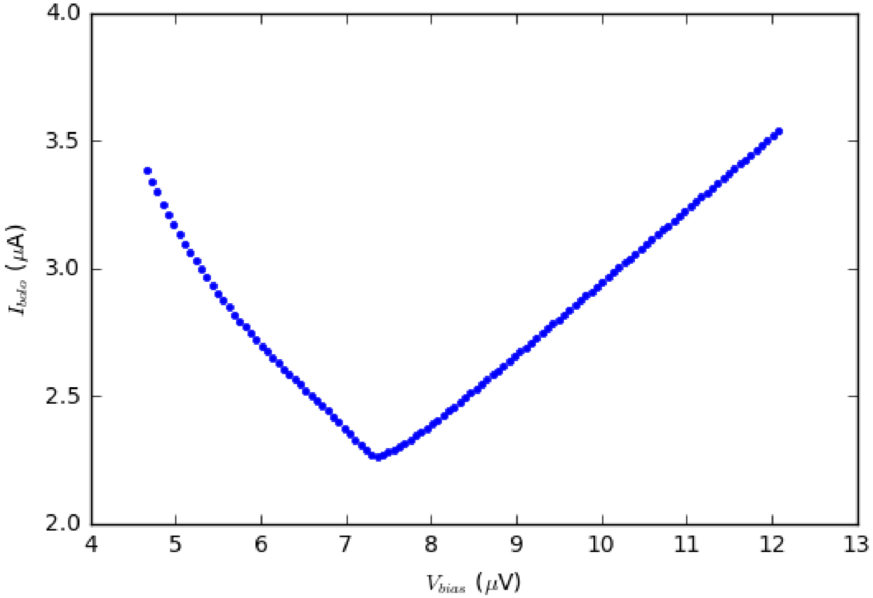
- **LC resonators**
  - Lithographed monolithic superconducting metal on silicon
  - Spiral inductors (L), interdigitated capacitors (C)

- **TES detector array**
  - TES bolometer with normal resistance of ~1 Ohm

[1] K. Rotermund et al., “Planar Lithographed Superconducting LC Resonators for Frequency-Domain Multiplexed Readout Systems,” JLTP 184 (2016)

Frequency multiplexing, IV Curve



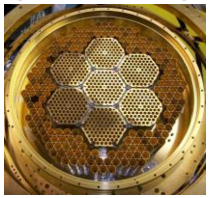


- **Multiplexing chip**
  - x40 (POLARBEAR-2/Simons Array), x68 (SPT-3G)
  - High 90’s % yield
  - Logarithmic frequency spacing for cross-talk
  - Resonant peak scatter meets cross-talk requirement ($\Delta f > 20$ kHz)
- **Bolometer tuning**
  - ~15,000 TES bolometers deployed and biased in field (SPT-3G at South Pole)

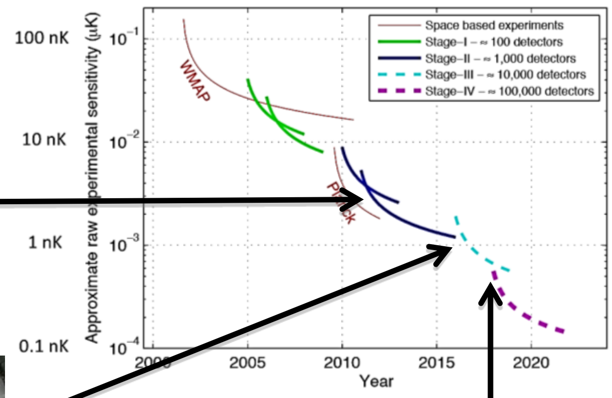
[1] Bender, A. N., Cliche, J.-F., de Haan, T. et al. [2014] “Digital frequency domain multiplexing readout electronics for the next generation of millimeter telescopes,” Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VII, p. 91531A, doi:10.1117/12.2054949, arXiv:1407.3161.

R&D for Next Generation Experiment

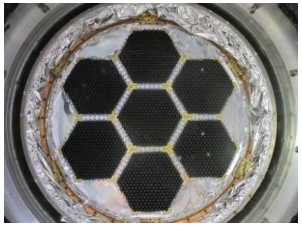
20 cm



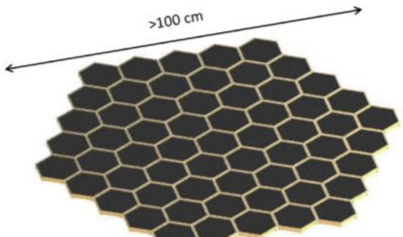
Stage-II
~1,000 detectors



35 cm



Stage-III
~10,000 detectors



Stage-IV
~500,000 detectors

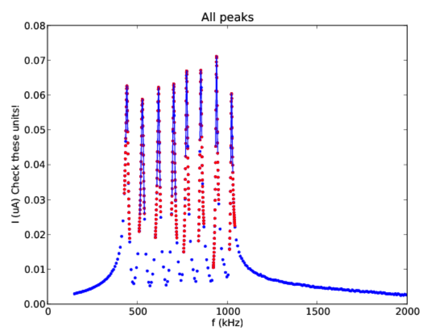
Detector count is increasing by order(s) of magnitude for next generation CMB experiment

1. Improve performance
2. Increase multiplexing factor
3. Simplify assembly process

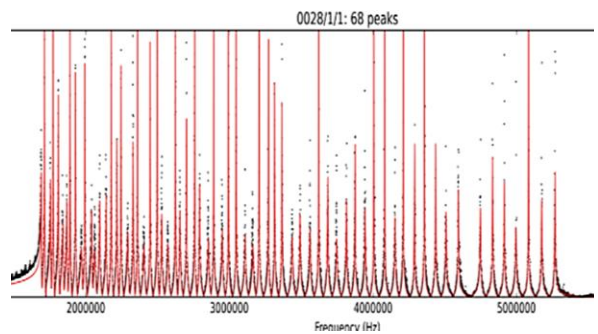
Stage-II (~1,000 det) to Stage-III (~10,000 det)

1. Increased multiplexing factor

- Increased total bandwidth
- Increased frequency comb packing density



x8 ~ x16 multiplex (< 1 MHz)

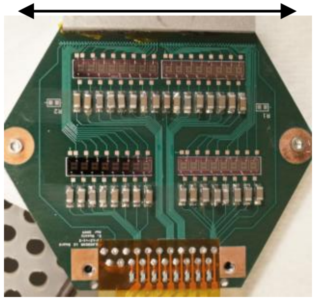


x40 ~ x68 mux (< 5.5 MHz)

2. Simplified assembly

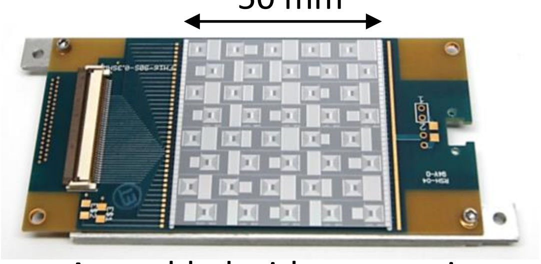
- Integrated more components onto a single chip
- Automated packaging by a company

80 mm



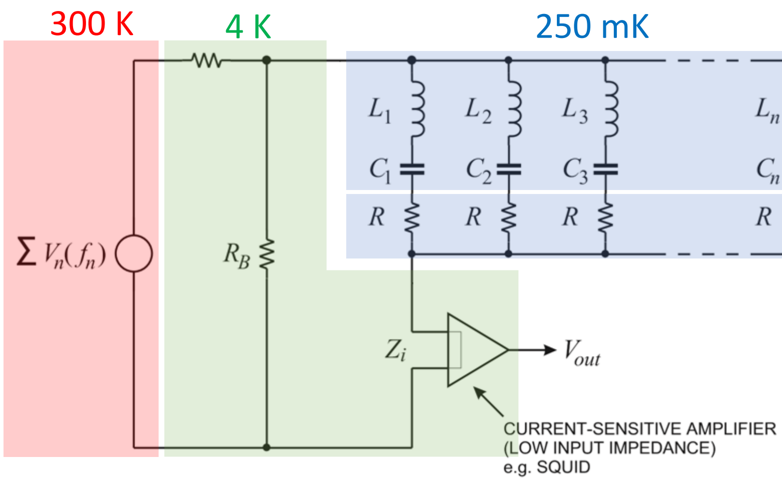
Hand soldered surface mount capacitor by students

50 mm

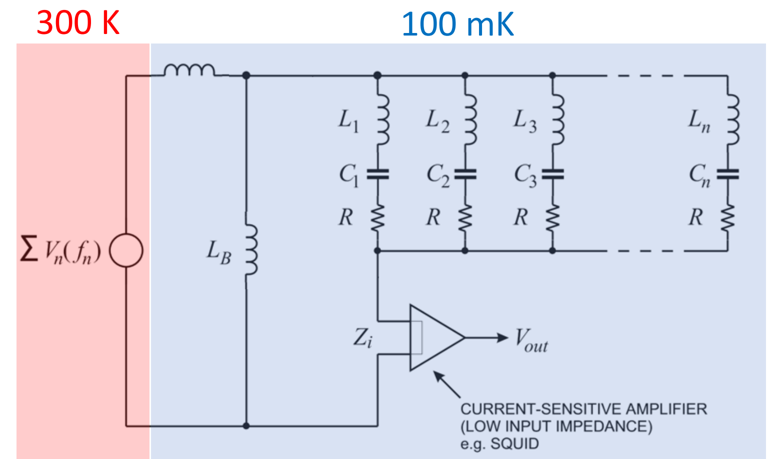


Assembled with automatic wire bonder by company

Improve Performance

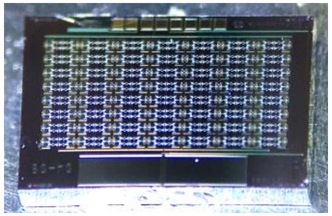


Current scheme



Bias Circuit + LCs + Detector Array at 100 mK stage

- **Reduce parasitic impedances**
  - Cables between temperature stages add parasitic impedance
    → Integrate components at mK stage
  - SQUID input coil
- **Key technologies:**
  - Reactive divider circuit
  - Low power dissipation SQUID
  - Low input inductance SQUID

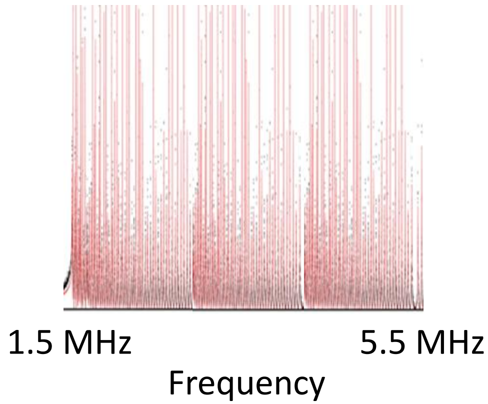


STAR Cryoelectronics

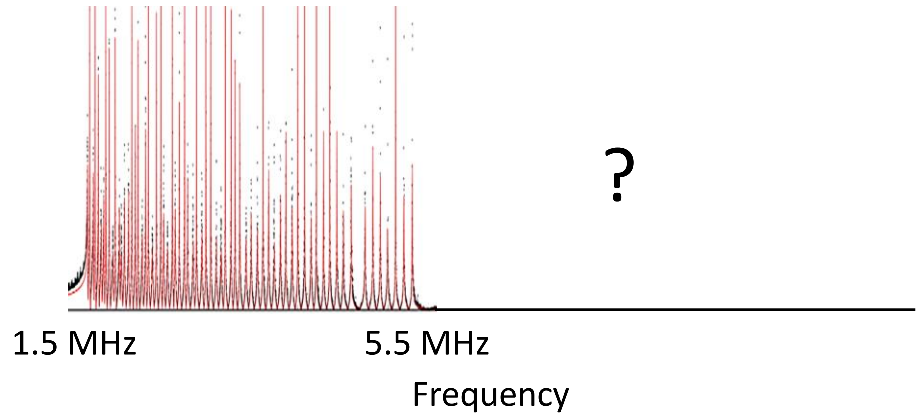
112 Series SQUID array fabricated by STAR cryoelectronics (Boyd et al.)

[1] Series SQUID Array Amplifiers Optimized for MHz Frequency-Domain Multiplexed Detector Readout, S. T. P. Boyd et al., LTD-17 (2017)

Increase Multiplexing Factor



Cartoon plot for increasing packing density

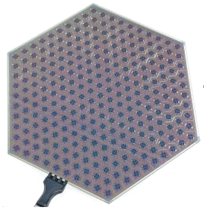


Cartoon plot for increasing total bandwidth

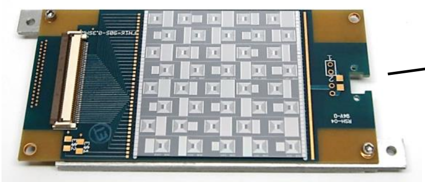
- **Increase frequency packing density**
  - Reduced parasitic allow higher packing density (log → linear spacing)
  - Learn to deal with cross-talk
    - Invert correlation matrix to deal with cross-talk in data analysis

- **Increase total bandwidth**
  - Reduced parasitic impedance allow us to explore higher frequency
  - SQUID operation at higher frequencies (SBIR: STARCryo)

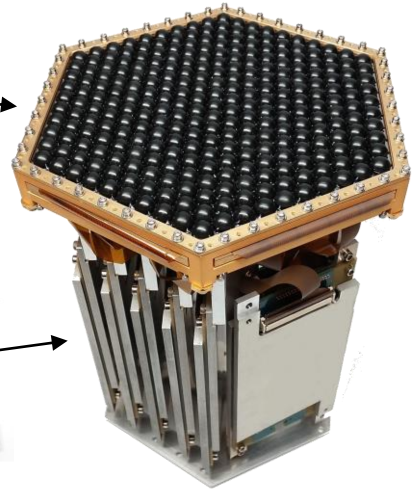
Simplify Packaging



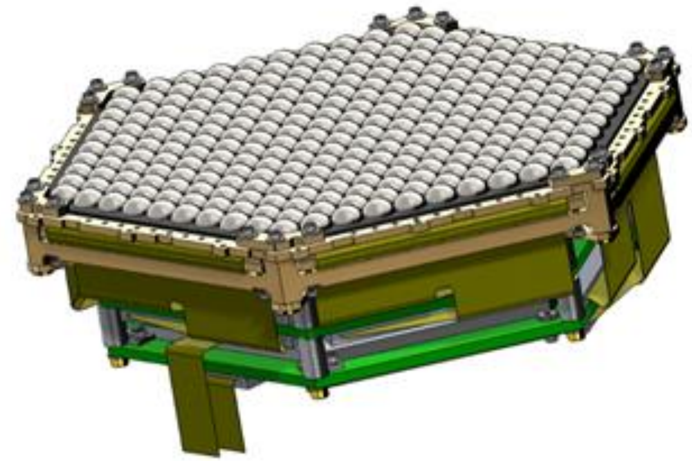
TES Detector Array

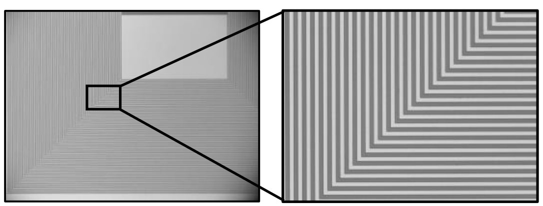


LC resonators (30 chips)

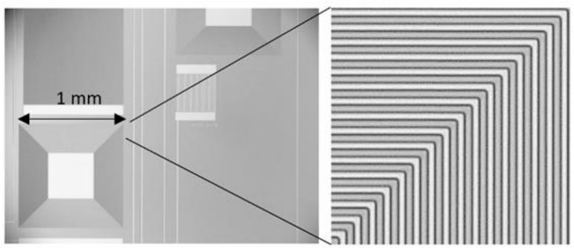


Detector Module





4 micron line inductors

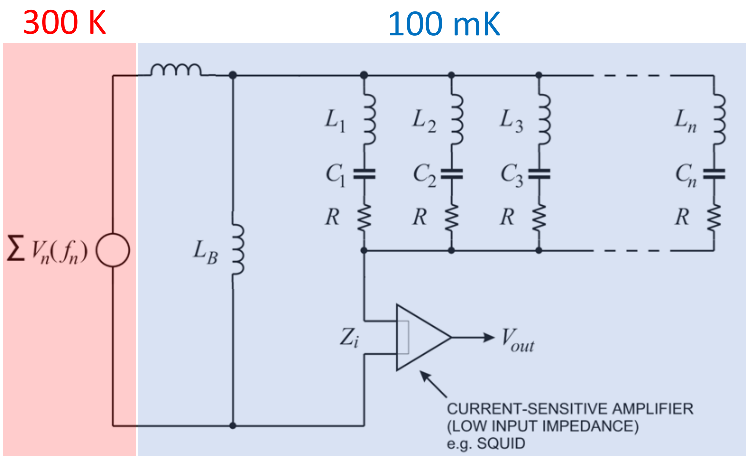


2 micron line inductors

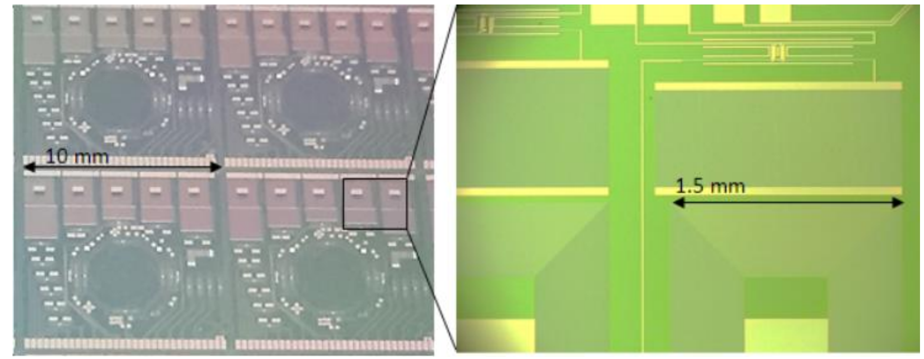
- **Reduce number of parts**
  - Increase packing density by decreasing component size
  - Push on resolution of lithography
  - Explore new lumped reactive element design (example: parallel capacitor)

[1] Lithographed Superconducting Resonator Development for Next Generation Frequency Multiplexing Readout of Transition-edge Sensors. Faramarzi et al., LTD-17 (2017)

Integrate with Detector Wafer



Bias Circuit + LCs + Detector Array
On a wafer



Prototype chips

HYPRES The Digital Superconductor Company™ STAR Cryoelectronics

- **Integrate cryogenic readout electronics and detectors on a single wafer, Microfabricate simultaneously**
  - Removes assembly process
  - Challenges:
    - Finite space on a wafer → R&D decrease component size
    - Compatibility of readout electronics fabrication and detector fabrication
    - Yield
  - Proto-type fabrication
    - LDRD support and SBIR with HYPRES and StarCRYO electronics

Summary

- Frequency multiplexing readout enabled multiple kilo-pixel CMB experiments
- Multiple developments were made to meet demand of current generation experiment

- Similar scale up will be important for next generation experiment
  - Improve performance
  - Increase multiplexing factor
  - Simplify packaging
  - Integrate readout electronics with detector wafer