Antenna-Coupled TES Array Development in Astrophysical Applications

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Overview

- Instrumentation requirements in Cosmic Microwave Background (CMB) polarization anisotropy
- Cryogenic detectors
- Antenna-coupled TES array architecture and characterization at Caltech/JPL
- TES array multiplexing and systematic issues
- Cryogenic detectors development at Argonne Lab
- Summary

Tools in Understanding the Universe

- Theories
  - Big Bang
  - Inflation
  - Baryogenesis
  - Nucleosynthesis
  - Recombination
  - Star formation, then galaxies, clusters of galaxies, …
- Tests
  - Hubble's law
  - Nucleosynthesis data
  - Structure formation history
  - Cosmic Microwave Background (CMB)

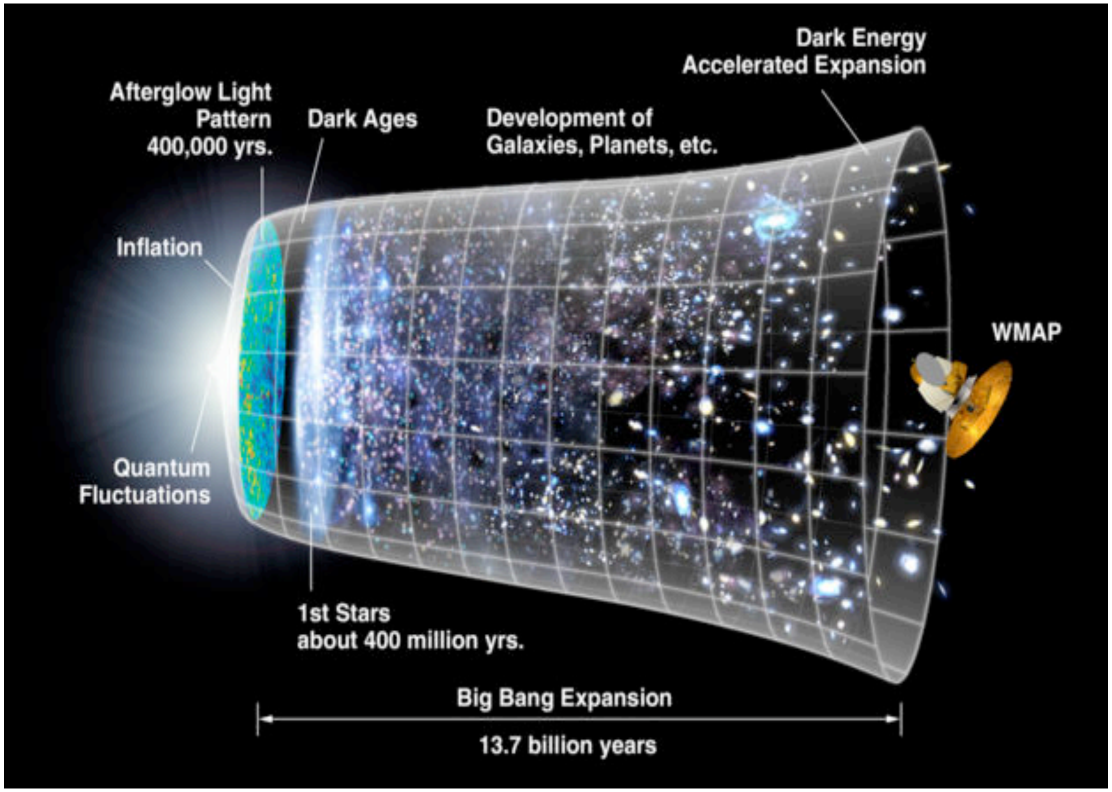
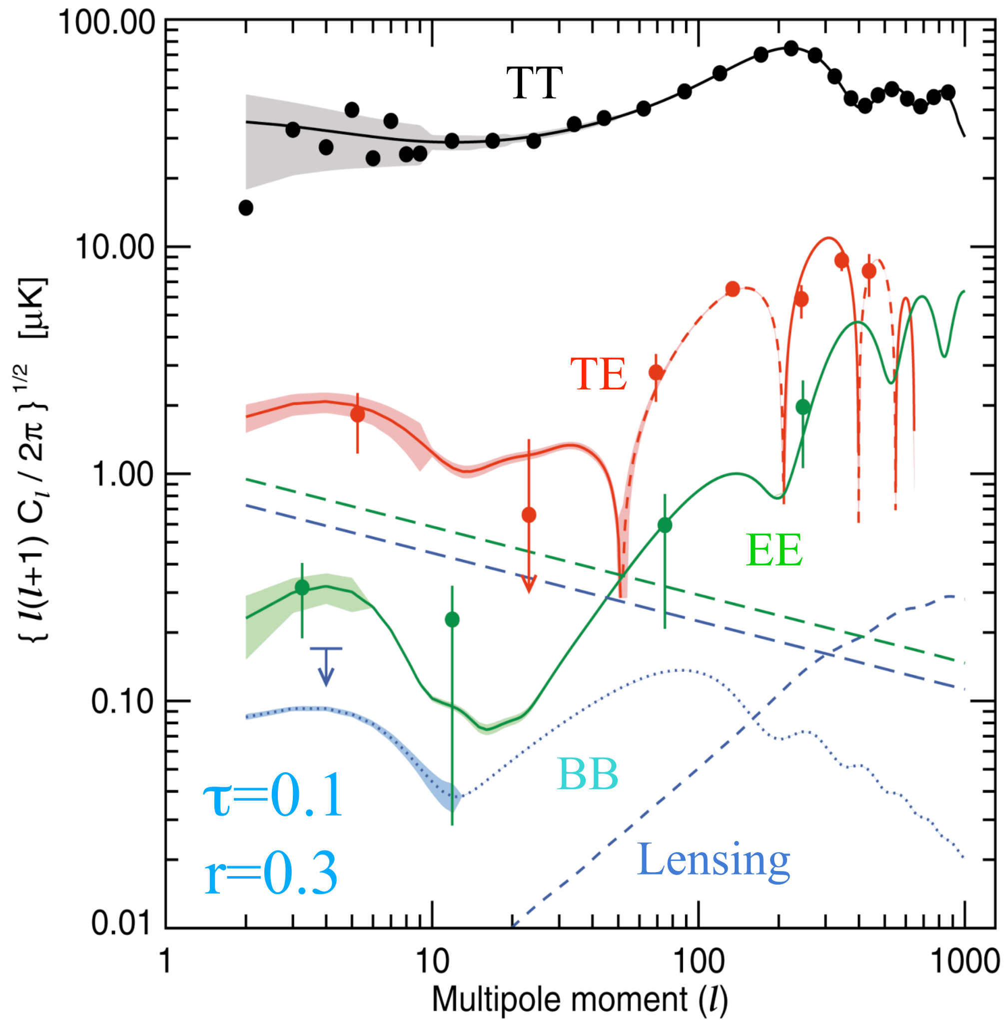


Image from WMAP press release

Status of CMB Observations

- CMB Blackbody Temperature
  - ☑ Observed
  - ☑ Well Characterized
- CMB Temperature Anisotropy
  - ☑ Observed
  - ☑ Well Characterized
- CMB E-mode Polarization
  - ☑ Observed (DASI, B03, CBI, CAPMAP, QUAD, WMAP)
  - – Not Well Characterized
- CMB B-mode Polarization
  - – Not observed, Possible by Planck, SPIDER, and SPTpol in future
  - – Not Characterized

WMAP Three Years Data

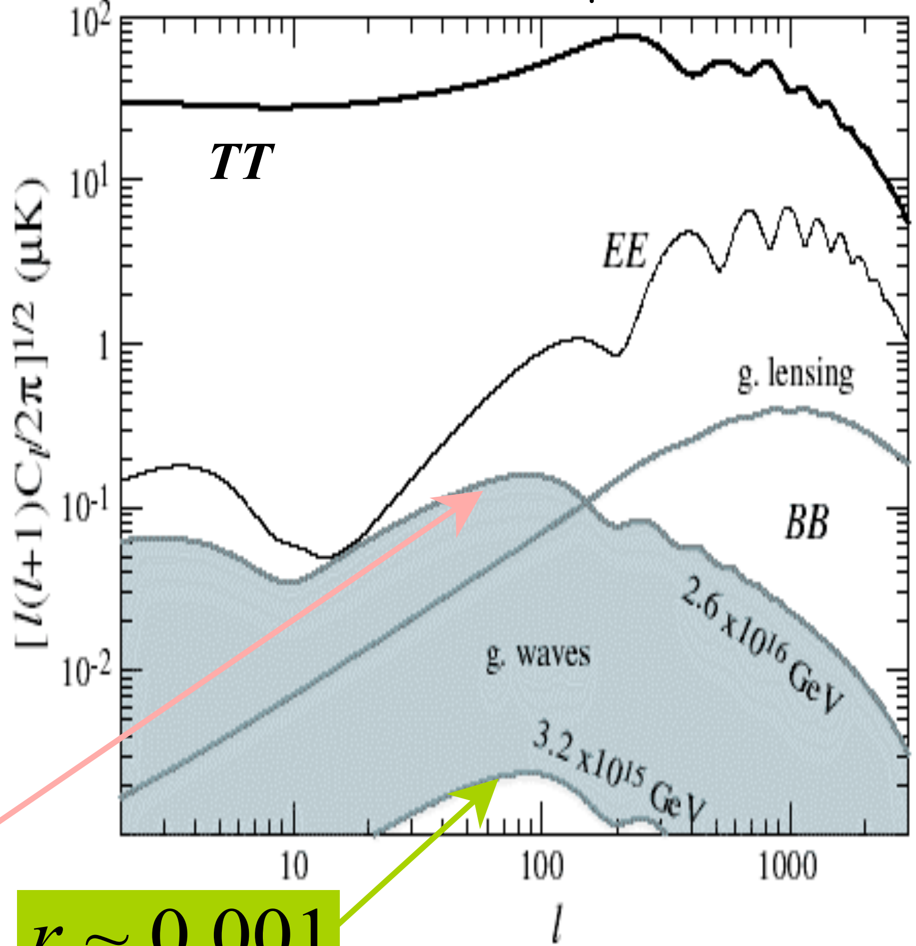


Why CMB B-mode Polarization Measurement?

- The fingerprint at the time of inflation (10^{-35} s) is encoded on the cosmic gravitational-wave background (CGB)
- Exploration and test of high energy physics in GUT
- CGB stretches and compresses spacetime on the surface of last scattering -- transmitting this information as a curl component in the polarization

$$r \equiv \frac{T^2}{S^2} \propto \left(\frac{E_I}{M_{pl}}\right)^4$$

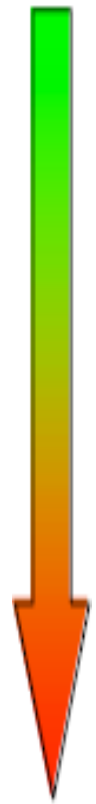
W. Hu et al. astro-ph/0210096



$r \sim 0.1$ $r \sim 0.001$

Detector Sensitivity for CMB B-Modes

- CMB temperature — $\langle T \rangle = 2.725K$
- CMB anisotropy angular power spectrum — $\Delta T_{rms} \sim 20\mu K$
- CMB polarization anisotropy angular power spectra
  - E-modes — $\Delta T_{E,rms} \sim 2\mu K$
  - B-modes — $\Delta T_{B,rms} \leq 0.1\mu K$

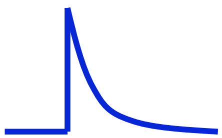


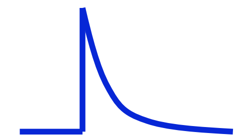
Increasing difficulty

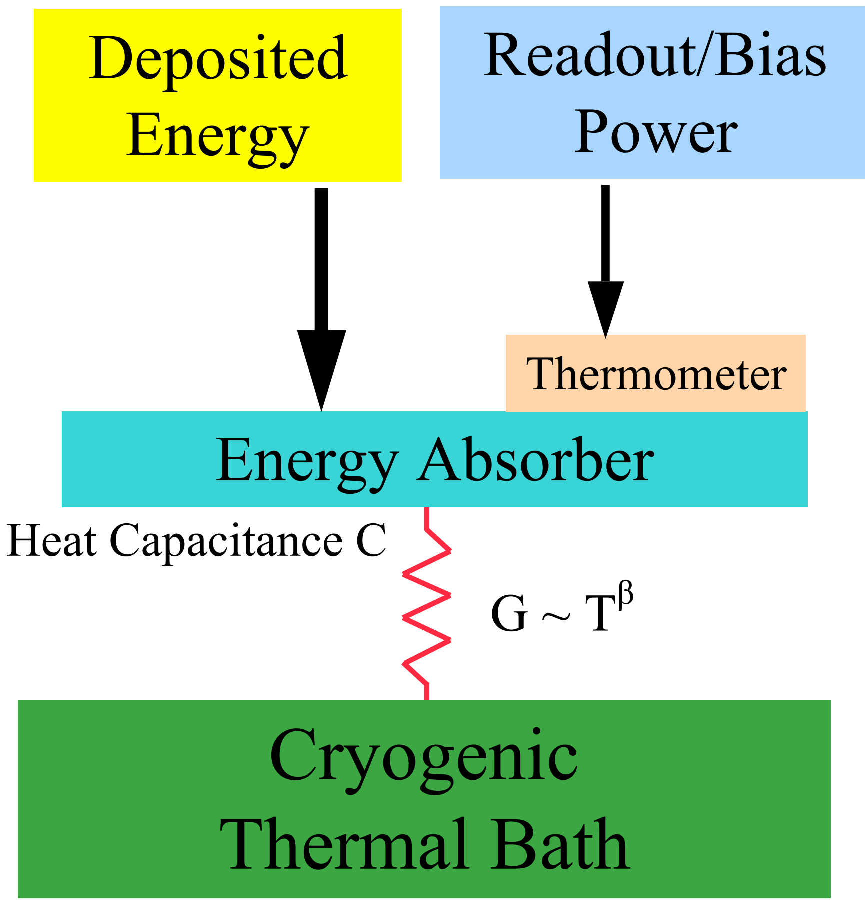
CMB Detectors

- Interferometric
  - measuring microwave electric field amplitude and phase at the same time
  - n-antennas (or telescopes), number of correlated channels is proportional to n^2
  - Moderate noise level ~ 1mK $Hz^{-0.5}$ for each antenna, and instrument sensitivity inversely scales with n
  - 4 ~ 20 K
- Coherent
  - Feed horns or waveguides, then OMT
  - Noise level is moderate: WMAP, 0.65 mK $Hz^{-0.5}$ at K; 1.48 mK $Hz^{-0.5}$ at W
  - 4 ~ 20 K
- Bolometric
  - Measuring microwave electric field amplitude
  - Feed horns or wave guides could be removed
  - Noise level is low, 0.1 ~ 0.2 $mKHz^{-0.5}$, as low as 0.03 $mKHz^{-0.5}$ in space operated below 0.1K
  - Large format receivers array with a single telescope
  - Below 1 K, cryogenic detectors

Cryogenic Detector Model





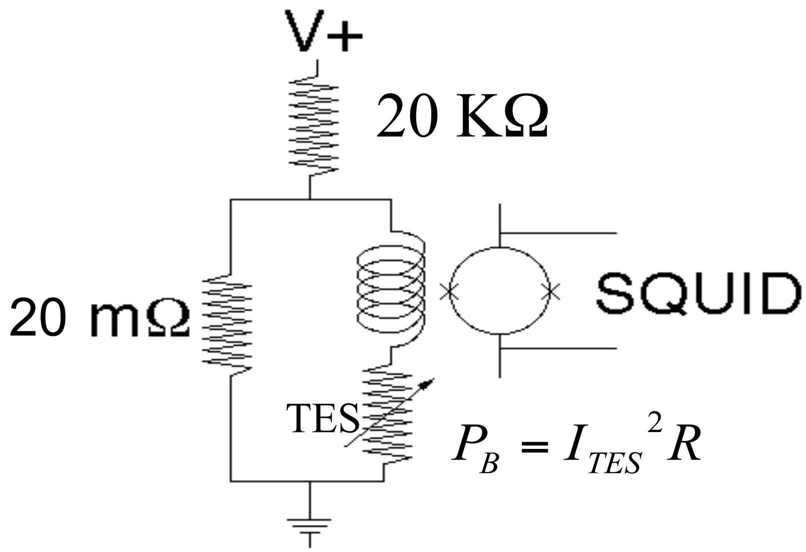


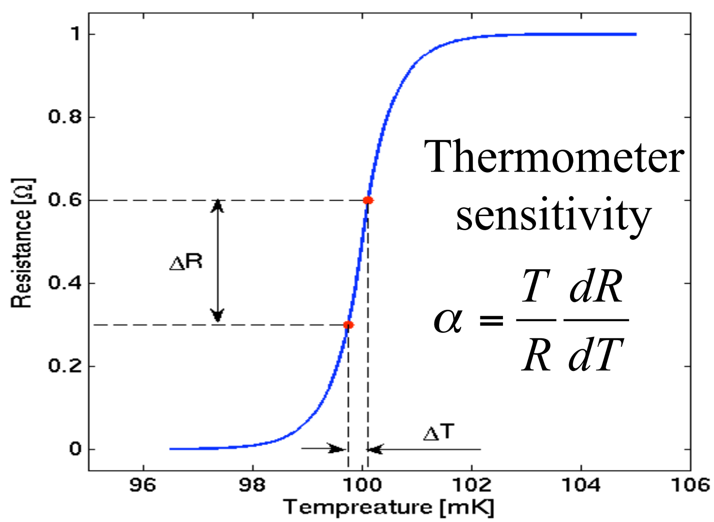
Energy coupling
- Antenna and/or microstrip
- High Z metal
- Semiconductor crystal

Thermal design
- Operated below 1K
- Absorber mass depends on energy to be measured
- Thermal link: direct substrate contact or connection with reduced thermal conductance

Thermometer
- Resistive: NTD, TES
- Junctions: SIS, NIS
- Magnetic: electron spin
- Inductance: MKIDs

TES Detectors





- Conventional superconductor film
- Voltage bias with a negative feedback
- Temperature change is converted to a current change

$$C\frac{dT}{dt} = P_B - G(T - T_b) + Q\delta(t)$$

$$\Delta I \approx -\frac{Q}{C}\frac{\alpha \cdot I_{TES}}{T}\exp\left(-\frac{t}{\tau}\right)$$

$$\tau \approx \frac{C}{G}\frac{1}{1+g} \qquad g = \frac{P_B\alpha}{GT}$$

$$S(\omega) \approx \frac{1}{V_B}\frac{1}{1+i\omega\tau}$$

Why TES Detectors?

- High performance thermometer
  - Sharp superconducting transition, good sensitivity
  - Voltage bias (electro-thermal feedback)
    - linear broad band response: up to a few tens kHz
    - Fast response time: a few tens μs ~ a few tens ms
    - Modest variations in Tc across wafer are accommodated
  - Low dissipation: TES + shunt resistor ~ 0.1nW
  - Low noise $NEP \sim 10^{-18} W / \sqrt{Hz}$
- Low impedance devices
  - Immune to microphonic noise
  - Impedance matching to SQUID amplifier's dynamic resistance
- Applications
  - Calorimeter and micro-calorimeters: particle detectors, for example CDMS; improved energy dispersive spectrometer in material science; constellation X-ray in astrophysics; radiation remote sensing
  - Bolometers: UV, visible, infrared, and millimeter photons

Review of Noise in CMB Measurement

- Noise specified as Noise Equivalent Power (NEP), power incident on detector that can be detected at 1σ in 1 sec, units of W $Hz^{-0.5}$
  - detector noise: phonon noise, Johnson noise of resistors, amplifier noise.
  - Background Limited Infrared Photodetector (BLIP) noise: shot noise on DC optical load
  - sky noise: variations in sky loading
- These yield Noise Equivalent Flux Density (NEFD): flux density (Jy) that can be detected at 1σ in 1 sec, units of Jy $Hz^{-0.5}$

$$\mathrm{NEFD} = \frac{\mathrm{NEP}}{\eta A \Delta\nu}$$

- Beam size defines Noise Equivalent Surface Brightness (NESB), units of (Jy/arcmin^2) $Hz^{-0.5}$

$$\mathrm{NESB} = \frac{\mathrm{NEFD}}{\Omega_{\mathrm{beam}}}$$

- Can then calculate Noise Equivalent Temperature (NET_{CMB}), units of (μK_{CMB}/beam) $Hz^{-0.5}$

$$\mathrm{NET_{CMB}} = \mathrm{NESB}\left(\left.\frac{dI_\nu}{dT}\right|_{T_{\mathrm{CMB}}}\right)^{-1}$$

- For diffraction limited optics

  And at Rayleigh – Jeans limit

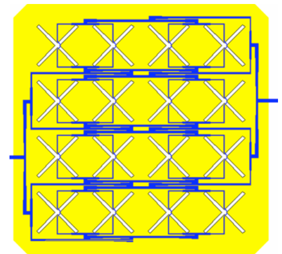
$$\mathrm{NET}_{\mathrm{CMB}} \approx \frac{\mathrm{NEP}}{2k_B \eta \Delta\nu}$$

Need Large Bolometer Array

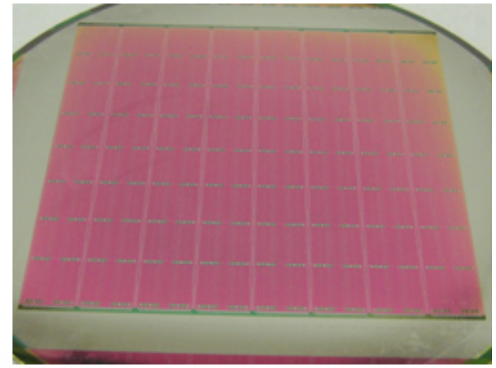
- TES bolometers are operated at 100~300mK
- Current fully instrumented bolometer NEP at 1e-18 W $Hz^{-0.5}$
- Photon noise NEP at about 5~8e-18 W $Hz^{-0.5}$ in space, and about 1e-17 W $Hz^{-0.5}$ near ground
- These can be transferred to CMB measurement sensitivity of 50~200 μK_{CMB} $Hz^{-0.5}$, which depends on bolometers operation temperature, instrumentation configuration, and frequencies
- To reach 1 μK_{CMB} $Hz^{-0.5}$ for B-mode CMB detection, 1000 or more bolometers are needed at each specific frequency band
- Compact photolithographic antenna-coupled TES bolometer large array

Large Detector Array

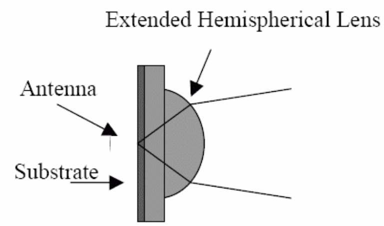
Antenna arrays
(Caltech/JPL)



Spider/SPUD

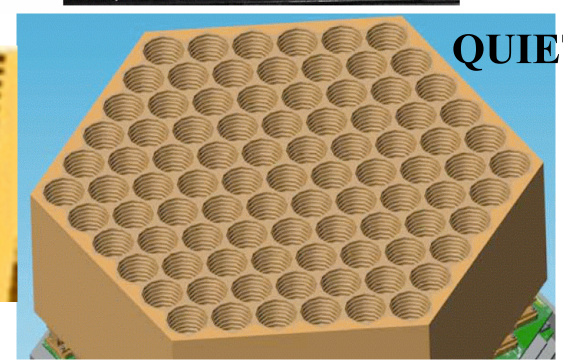


Lenslets (Berkeley)



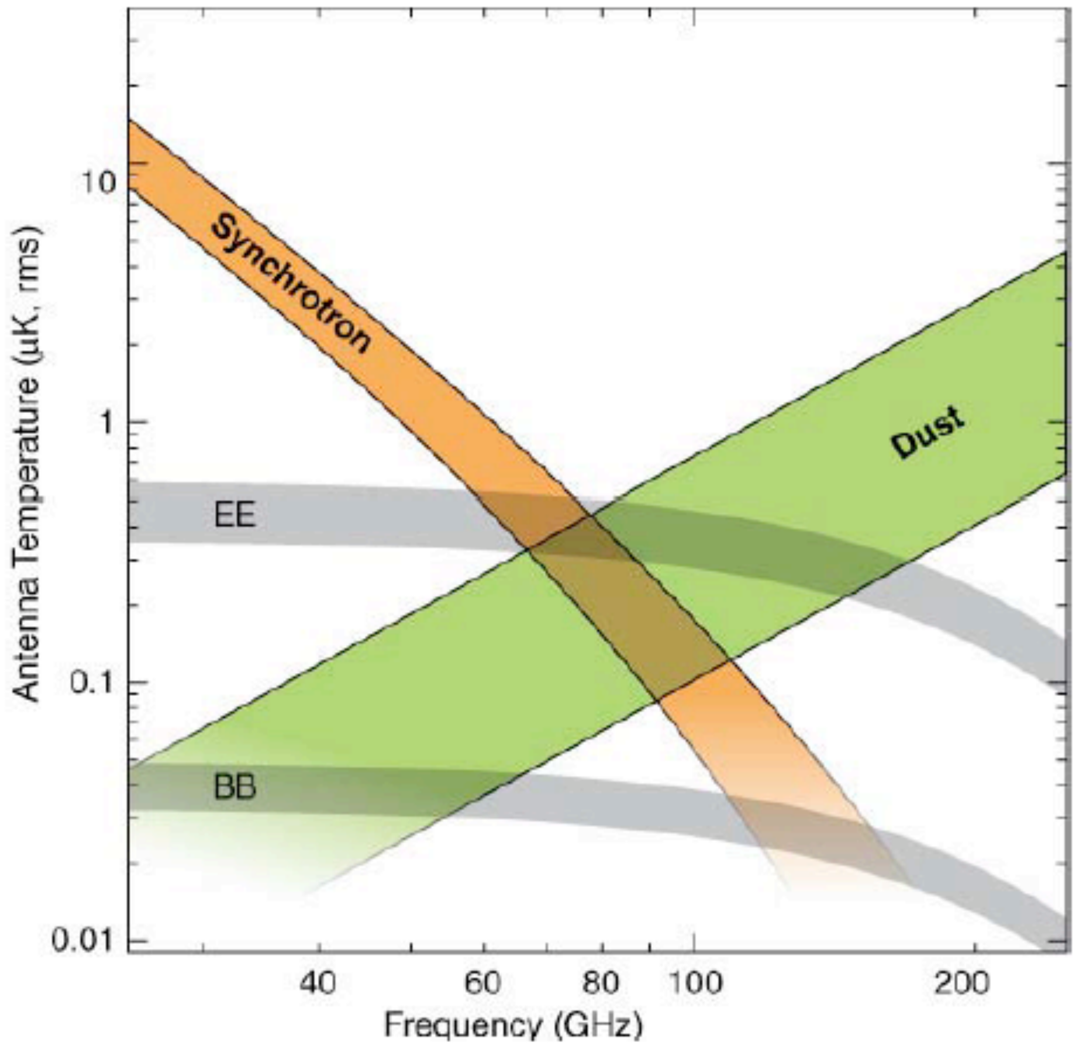
Polarbear

Platelets (U of C)



QUIET

Multi – bands for Foreground Subtraction



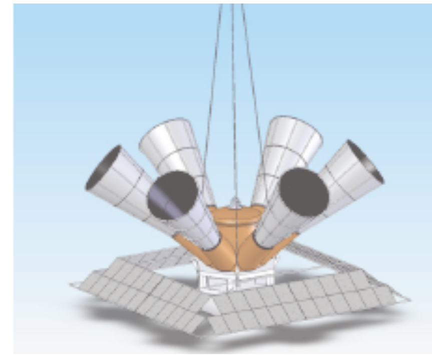
Task Force Report on CMB Research

For r = 0.01, more than 10 fold background reduction needed

Need multi-frequency bands for foreground subtraction

SPIDER: Balloon Borne Flight

CMB polarization B-mode measurement pathfinder: a large angular scale millimeter wave polarimeter with antenna-coupled TES large format arrays suitable for multiplexing



Observing Band (GHz)	Band width (GHz)	Beam FWHM (arcmin)	Number of Spatial Pixels	Number of Detectors	Single Detector Sensitivity (μK_{CMB} $Hz^{-0.5}$)	Instrument Sensitivity (μK_{CMB} $Hz^{-0.5}$)
80	19	72	100	200	110	7.8
100	24	58	2×144	2×288	100	4.2
145	35	40	256	512	100	4.4
225	54	26	256	512	204	9.0
275	66	21	256	512	351	15.5

Assume the overall optical efficiency 50%. Operated at 250mK

Format Receiver Arrays

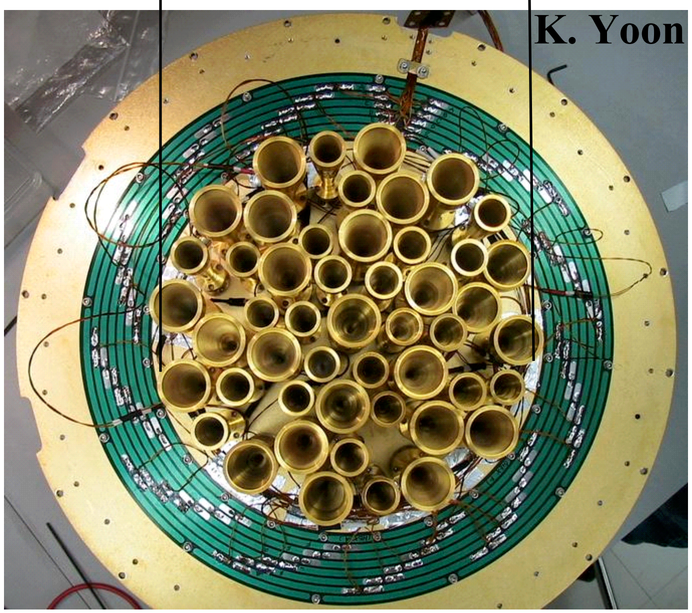
The state-of-the-art:

- Discrete elements: feeds, filters, detectors
- Massive and expensive, hand-assembled
- Low packing efficiency
- Individual JFET readout with moderate noise

The future:

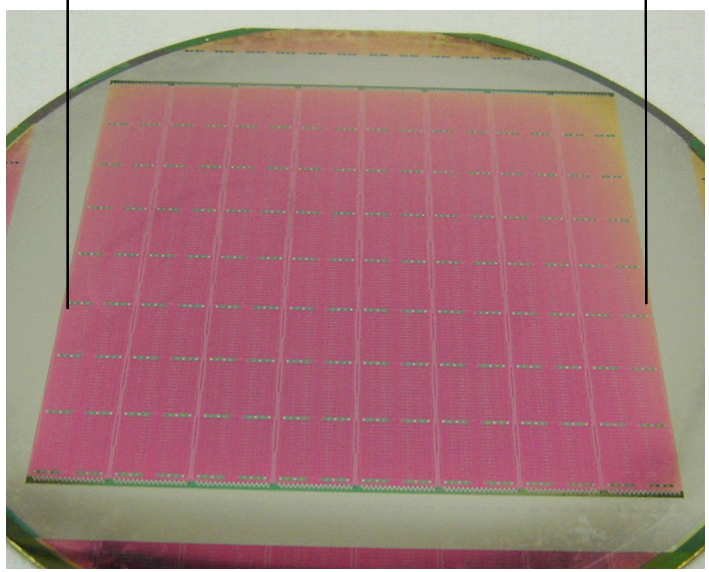
- Integrating all components on a Si wafer
- Compact, inexpensive, photolithographic
- High packing density
- TES low impedance enables SQUID multiplexed read-out with low noise

30 cm



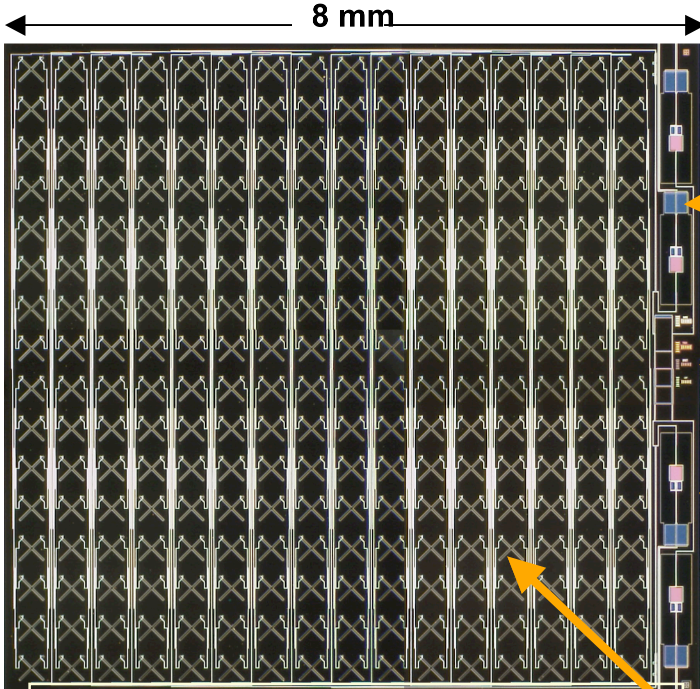
BICEP focal plane (98 detectors)

8 cm

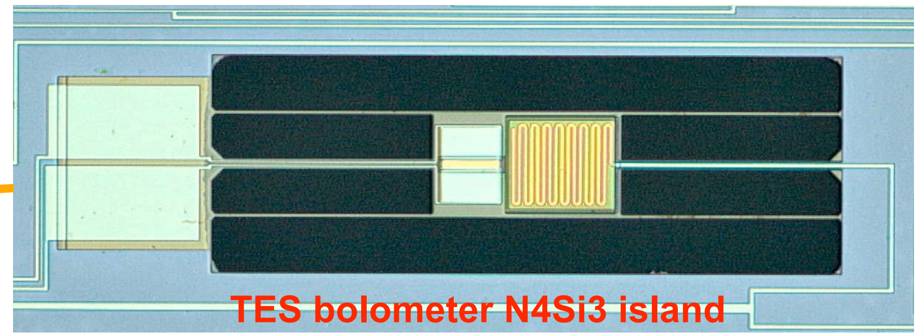


Antenna-coupled TES array (256 Q/U detectors)

150 GHz Dual Polarization Antenna Coupled TES

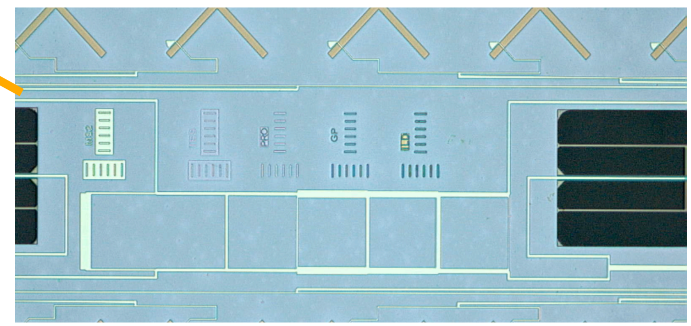


Beam synthesizing antennas with low loss Nb microstrips

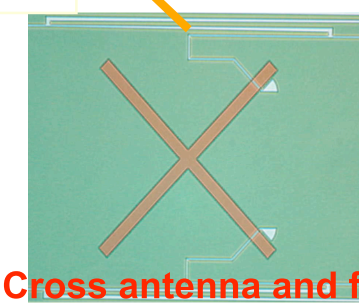


TES bolometer N4Si3 island

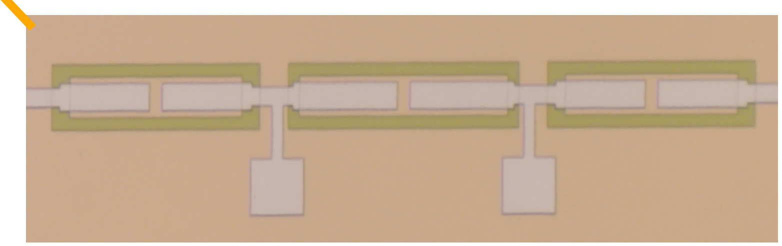
Modulator for simultaneous Q/U measurements



X shape antennas with feed at the ends

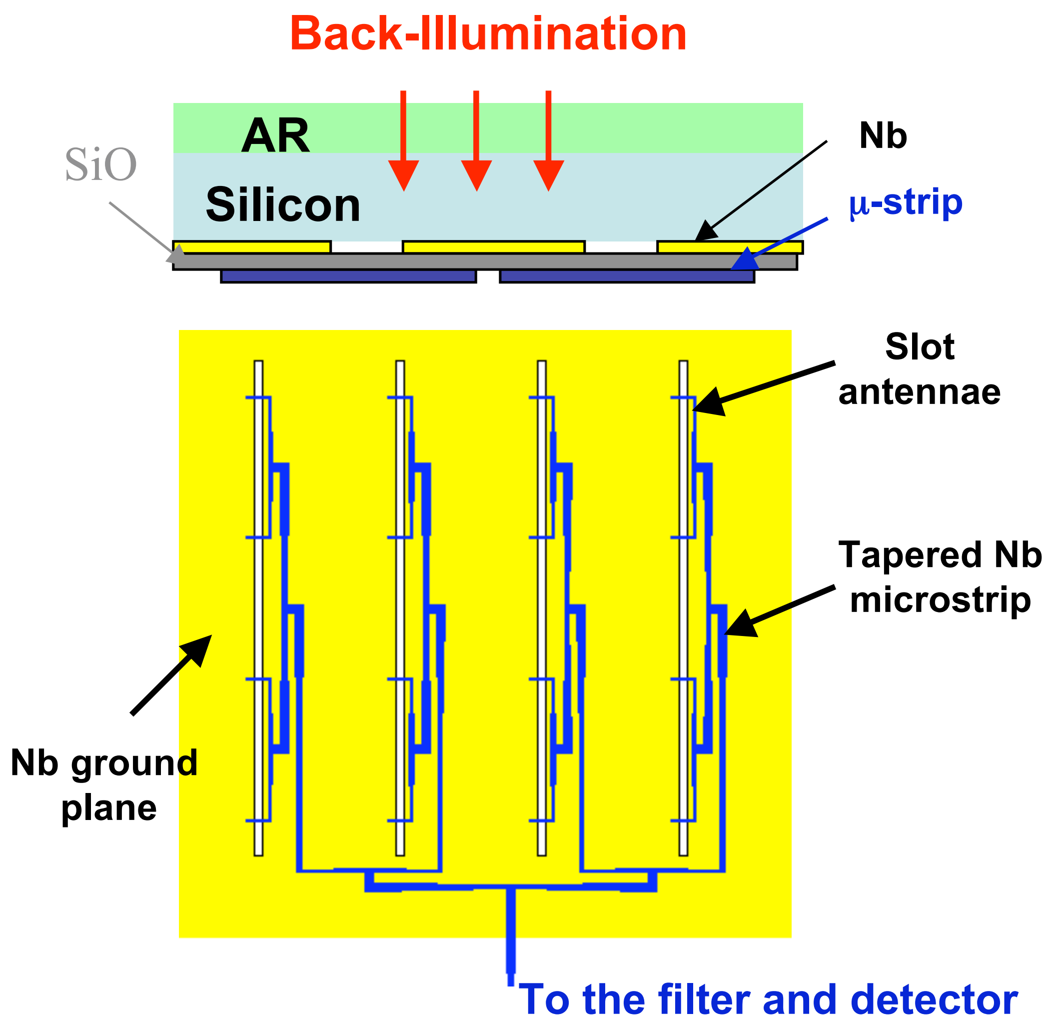


Cross antenna and feed



25 % Bandwidth Filter

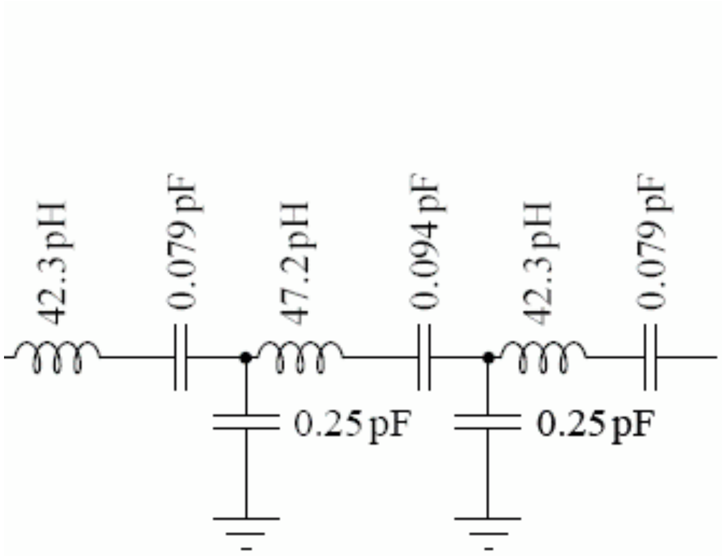
Single Polarization Antenna Architecture

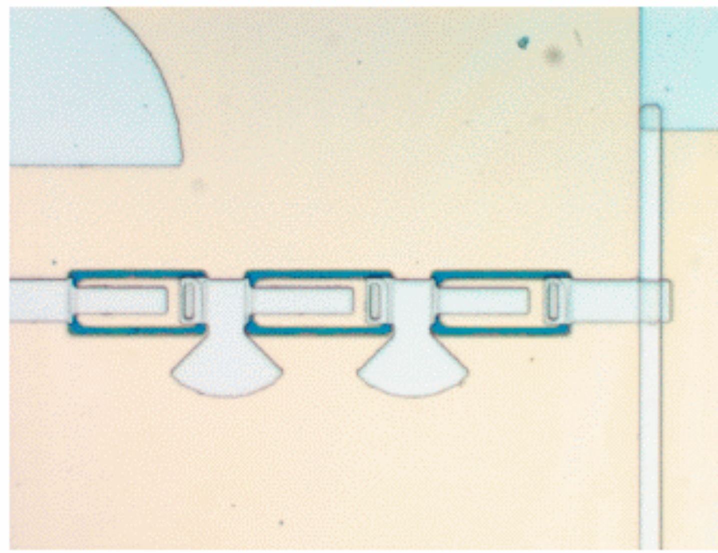


- Long slot antennas on the Nb ground plane provide beam collimation
- low loss Nb microstrip is coupled to slot antenna with stubs or vias
- Tapered Nb binary sum tree transport microwave to filters and detectors
- 50~500 GHz achievable
- Evaporated dielectric SiO
- Compact planar design with contact microfabrication

Filter

- Lithographic LC filter defines the band pass
- Nb (ground plane) – SiO – Nb (microstrip elements) structure
- 25% Bandwidth

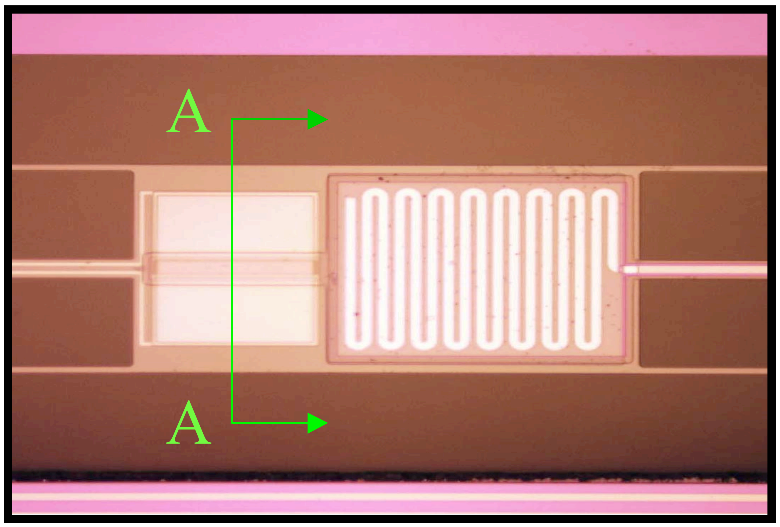


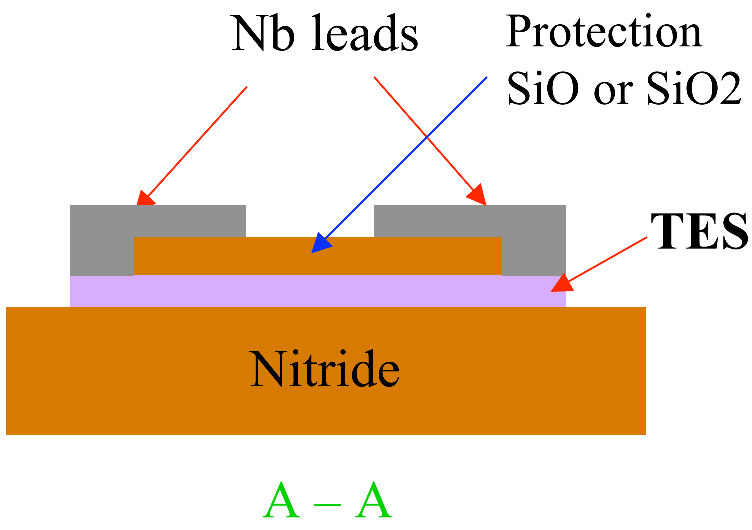


Designed by A. Goldin

Bolometer

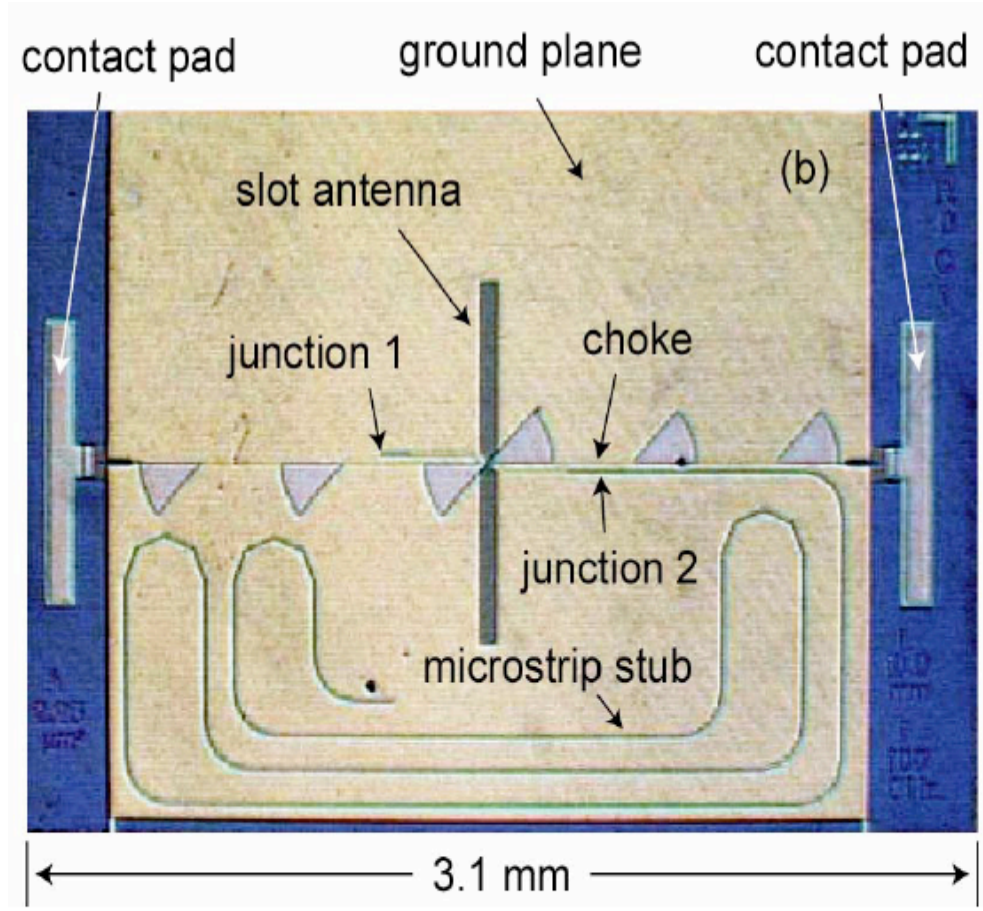
- Bolometer released by deep reactive ion etch
- Nitride legs support nitride membrane island
- Lossy metal microstrip as termination – wide bandwidth
- Superconducting transition edge sensor
- Quick thermalization time, fast bolometer relaxation time constant





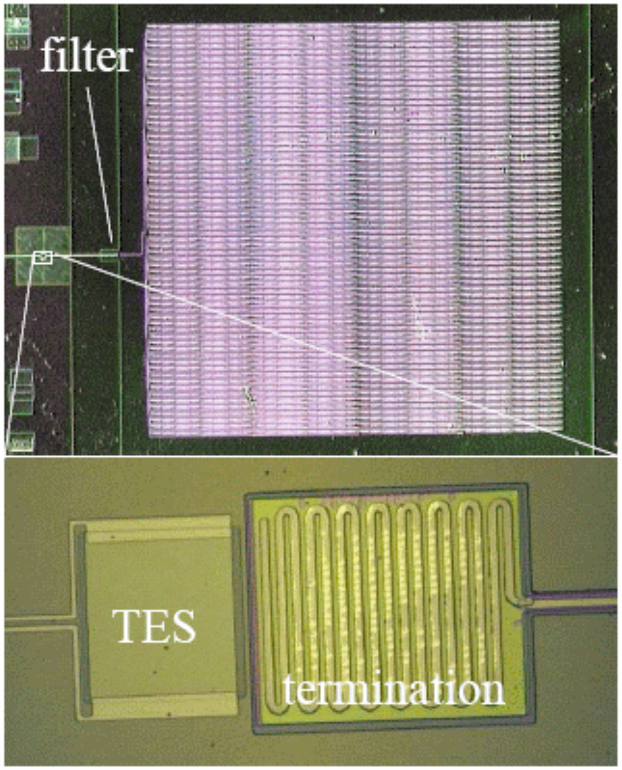
Microstrip Loss

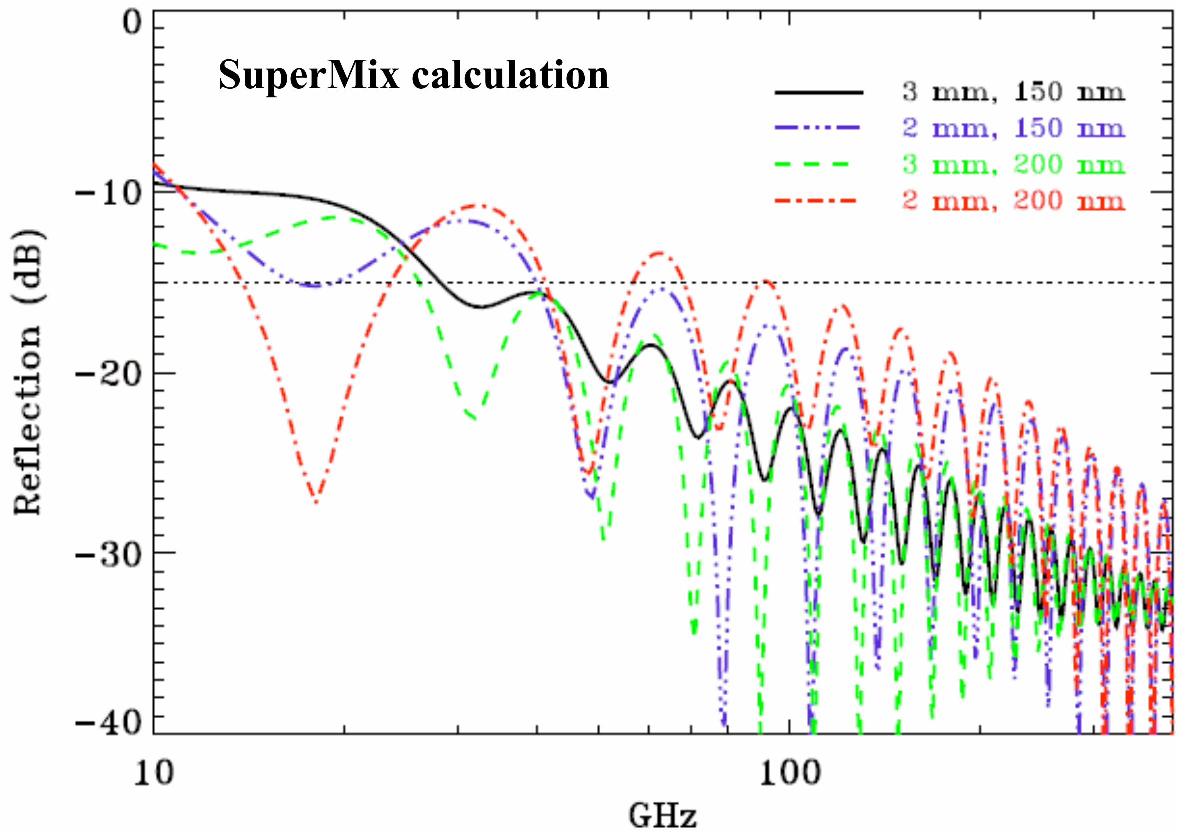
- Tested with SIS junctions at 4.2K and 1.5K
- The loss tan is $1.2 \pm 0.3 \times 10^{-3}$
- The amplitude 1/e attenuation length is 30~40cm, corresponding about 12% loss for 100 GHz detector
- The main loss comes from dielectric (two level systems)



100 GHz test chip with 11.4 mm long Nb/SiO/Nb microstrip stub. A. Vayonakis

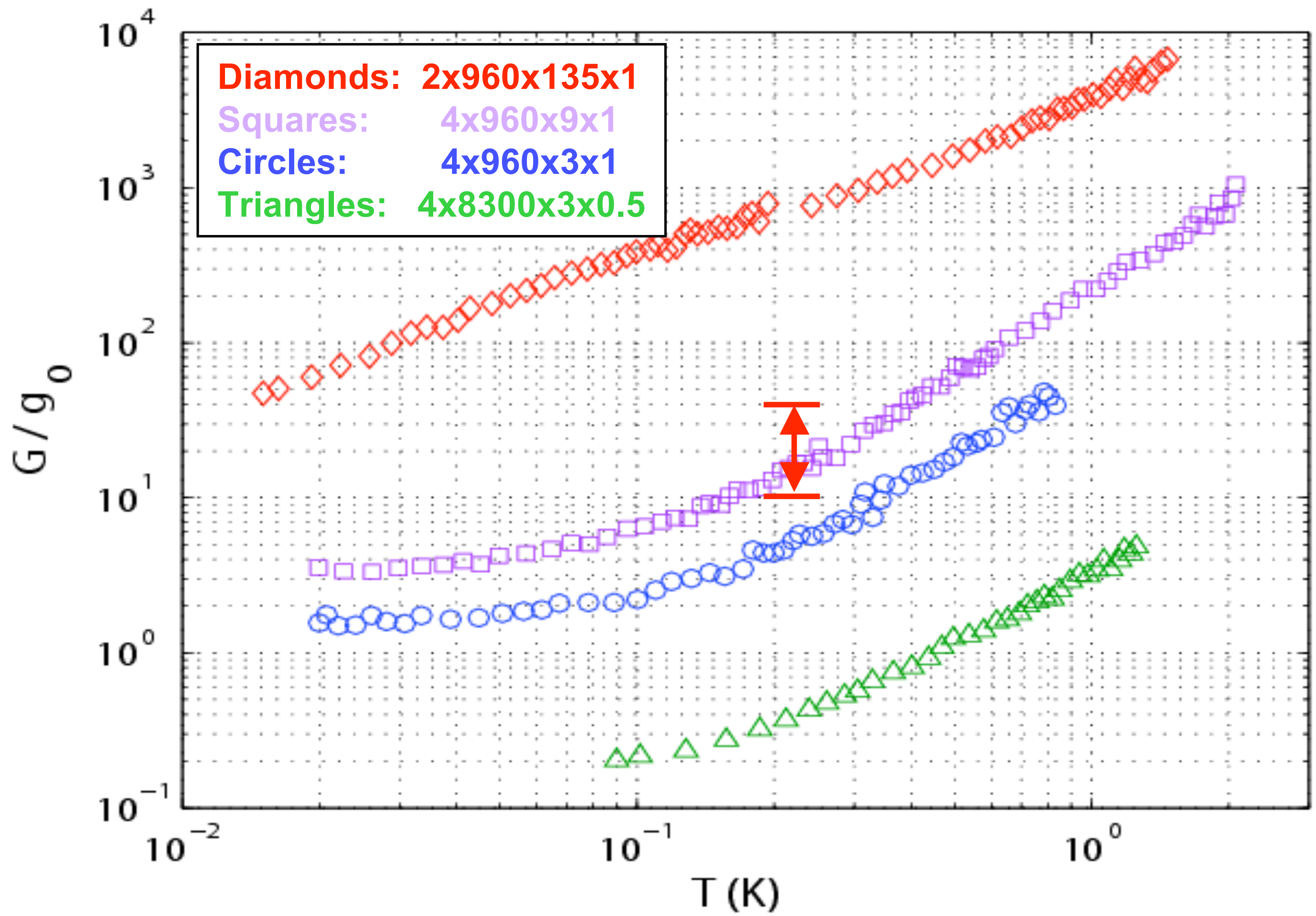
Wide Band Termination





- The meandering absorbing microstrip has > 99% absorbing efficiency over 30% bandwidth
- Very tolerant to fabrication variations, e.g., thickness or resistivity

Nitride Legs



$g_0 = \pi^2 k_b^2 T/3h \sim 1\text{pW/K}^2 \times T$ **SPIDER G/g_0 = 10-50 at 250 mK**

Microfabrication

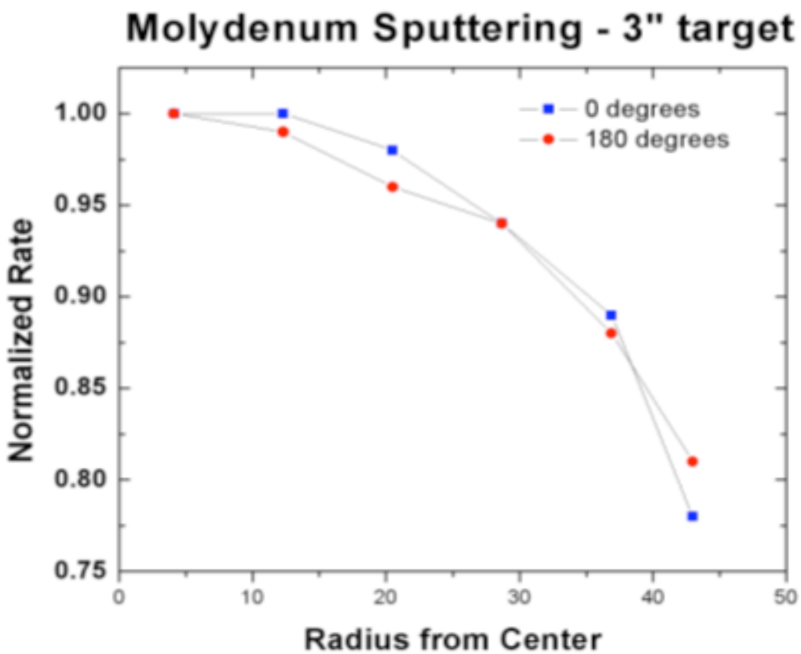
- Metallization
  - UHV sputter deposition systems
  - Current materials set: Nb, Al, Ta, Mo, Ti, Cu, Au, NbN, NbTiN
- Dielectric
  - LPCVD – low stress silicon nitride
  - Sputtered SiO_2 with substrate bias and O_2 compensation.
  - Evaporated SiO.
- Lithography
  - Stepper λ=248nm, 0.25μm resolution
  - Contact lithography: λ=436, 365, 320 nm
- Etch
  - 1 Chlorine chemistry, 1 Fluorine chemistry – 75mm, 100mm, 150mm wafers
  - STS deep trench reactive ion etcher - DRIE

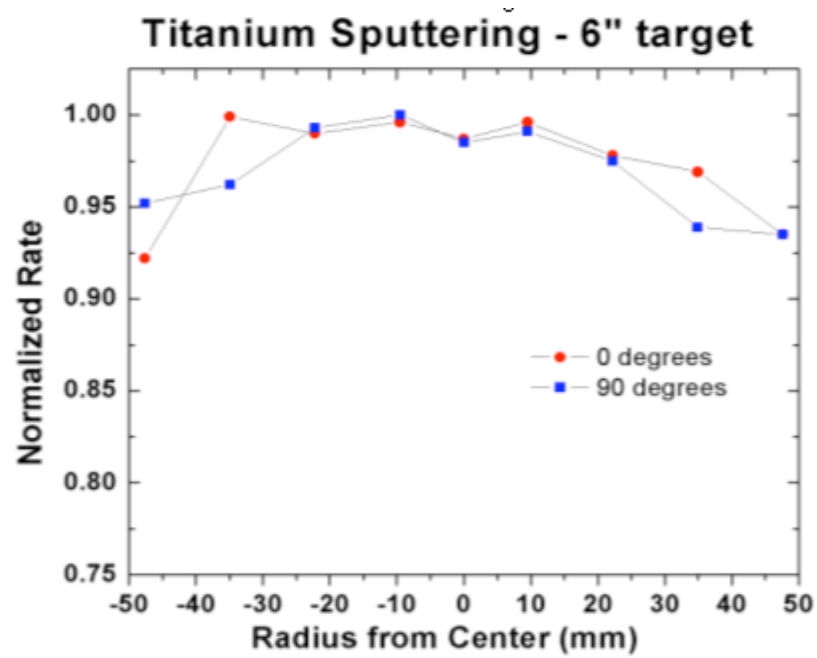
Multi-layer Structure Processing

	Layer	Etch/Lift-off	Material	Thickness
1.	Support legs pre		Si_3N_4	1000nm
2.	Ti-TES	CCl_2F_2/O_2 etch	Ti	250nm
3.	Protect	CHF_3/O_2 etch	SiO or SiO_2	150nm
4.	Ground Plane	CCl_2F_2/O_2 etch	Nb	150nm
5.	ILD	CHF_3/O_2 etch	SiO or SiO_2	300nm
6.	Resistor	Lift-off	Au	150nm
7.	Resistor Protect	Lift-off	SiO	150nm
8.	Microstrip	CCl_2F_2/O_2 etch	Nb	400nm
9.	FSN	BCl_3/Cl_2 etch	Al	500nm

Metallization (grey) Dielectric (cyan)

TES Uniformity



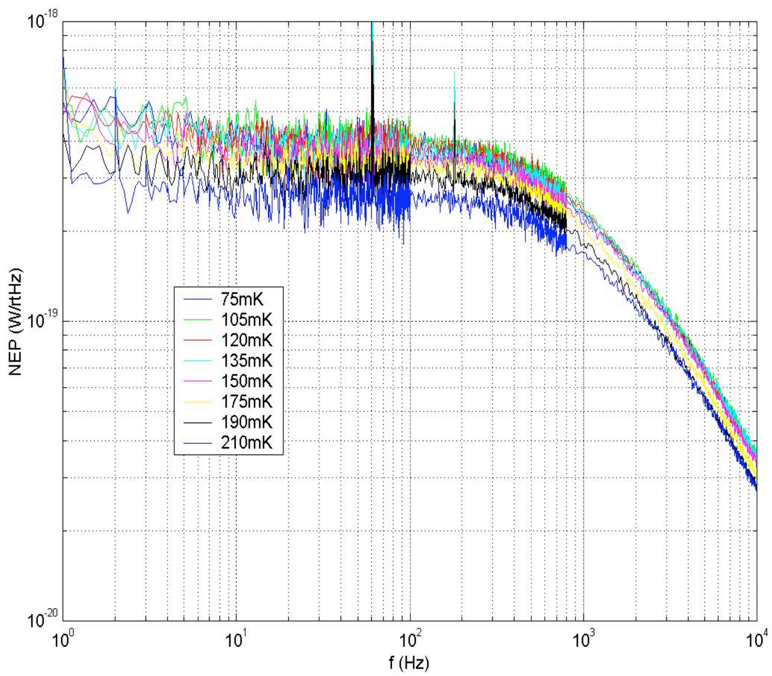


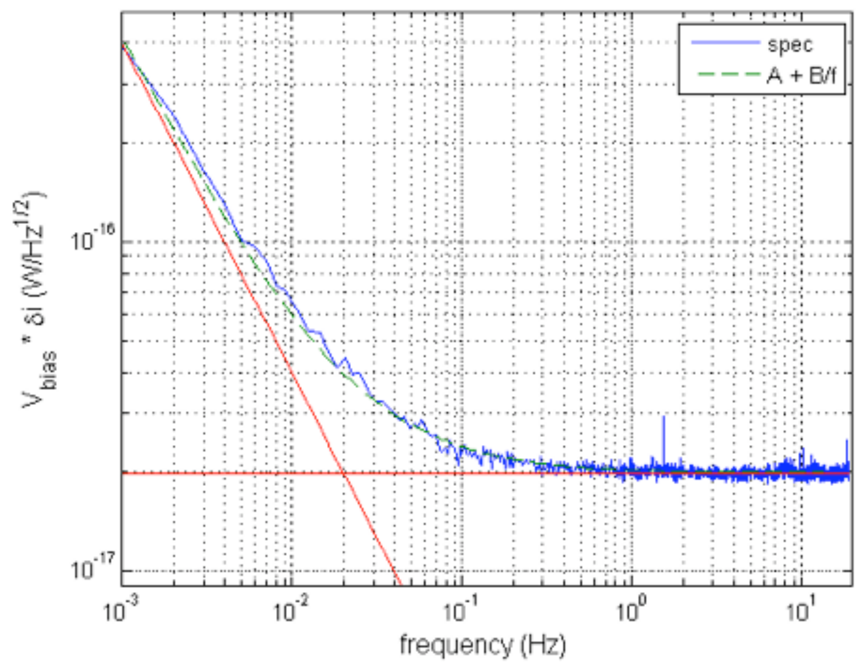
- TES transition temperature could change dramatically with metal film thickness and the contents of impurity contaminations
- Increase sputtering gun (target) radius, could control the superconducting film thickness uniformity with other sputtering parameters tuning
- Devoted facility to avoid impurity contaminations
- The target is to control Tc within 95% for Ti

Detectors Performance (Dark Tests)

- Mo/Au bilayer, Tc ~ 220 mK
- G ~ 1pW/K
- NEP ~ 3x10^{-19} W Hz$^{-1/2}$ $\propto \sqrt{4k_B G T^2}$
- 1/f knee < 1 Hz
- Rolling off frequency 800Hz $\propto$ G/C

- Ti/Al dual transitions, Tc ~ 450 mK
- G ~ 50 pW/K
- NEP ~ 2x10^{-17} W Hz$^{-1/2}$
- 1/f knee ~ 50 mHz
- Rolling off frequency > 1000Hz



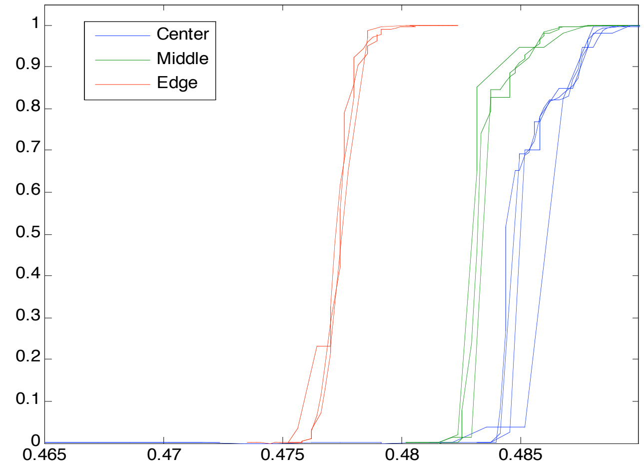


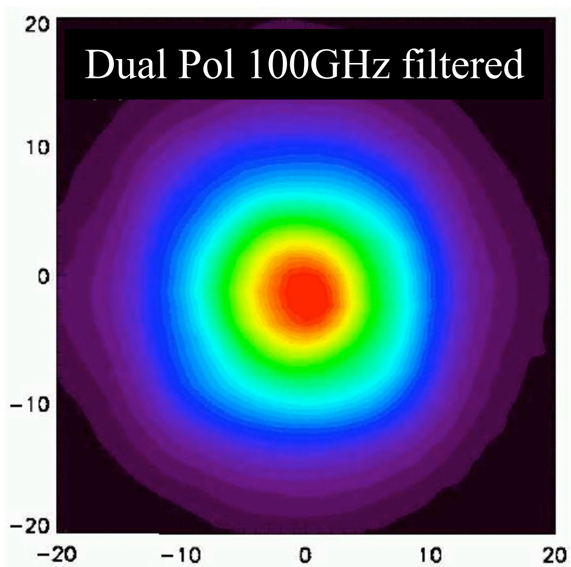
Antenna-Coupled TES Test facility

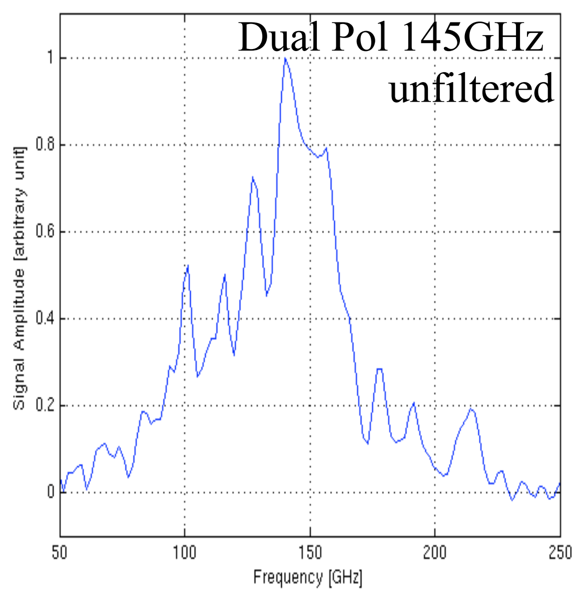
- 3 stage He absorption refrigerator with base temperature of 220mK
- Niobium shielding
- Optical windows
- Internal black body for optical efficiency test
- AC resistance bridges for thermometry
- PID temperature control
- Six channels of quantum physics SQUIDs
- Lock-ins: Stanford research
- Fourier transformation spectrometer
- Home made beam mapper

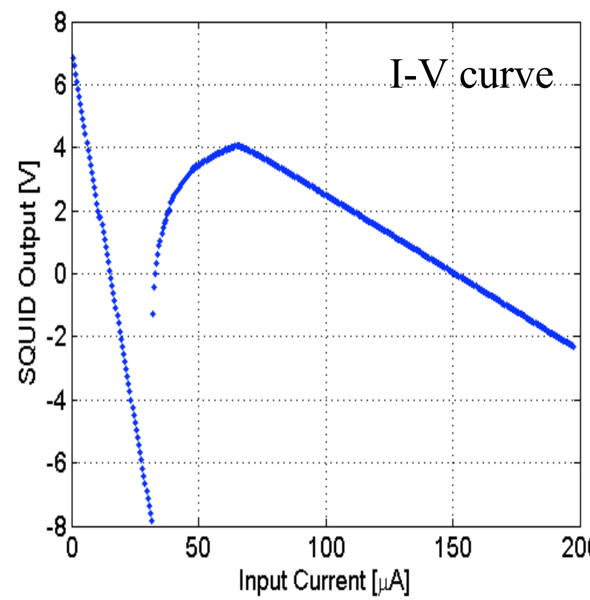
Test Tasks

- Tc measurements
- Antenna beam characterization
- Antenna spectrum and band pass filter characterizations
- Optical efficiency of antenna-coupled TES detectors





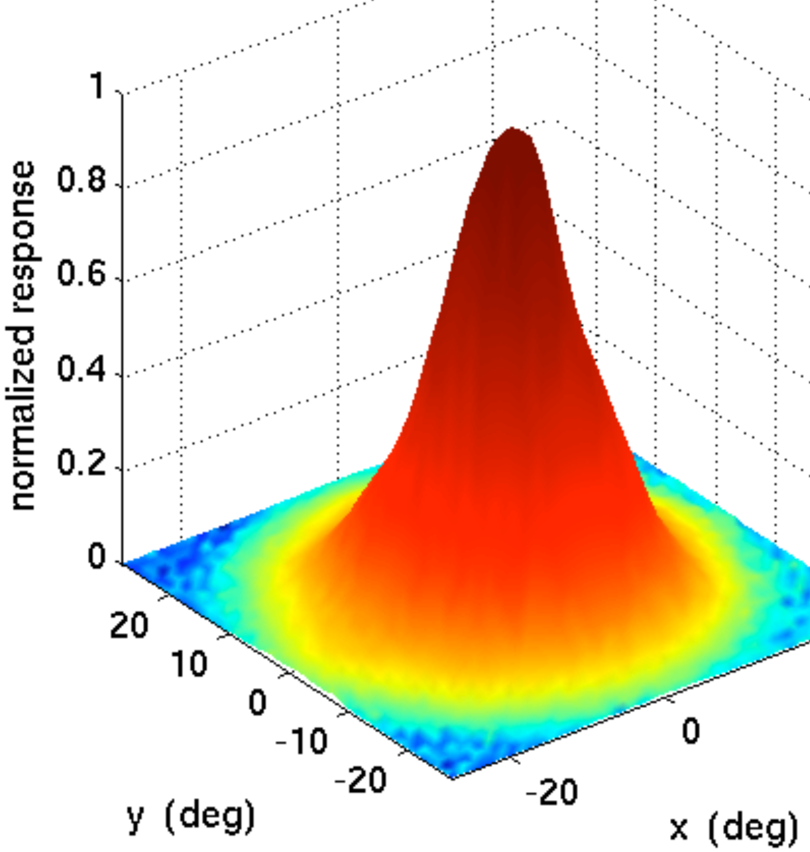


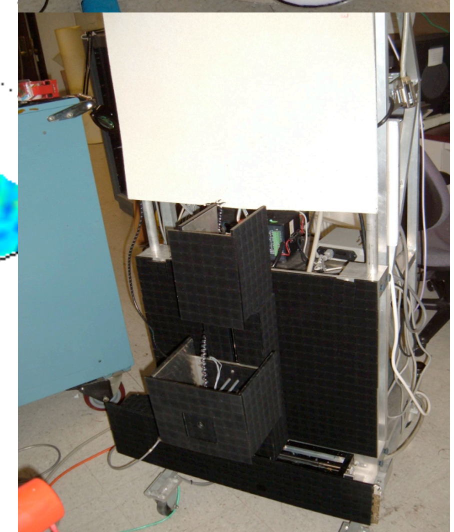


Beam of Antenna

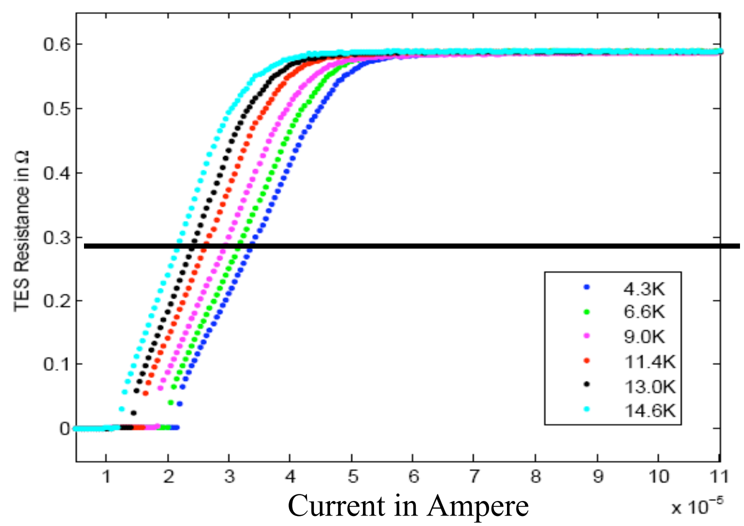
- Thermal source
- Two dimensional mapping
- 13.6° ± 0.1 ° Gaussian beam at FWHM
- Ellipticity < 3%
- Cross polarization < 5%
- Low sidelobes (out of view here)

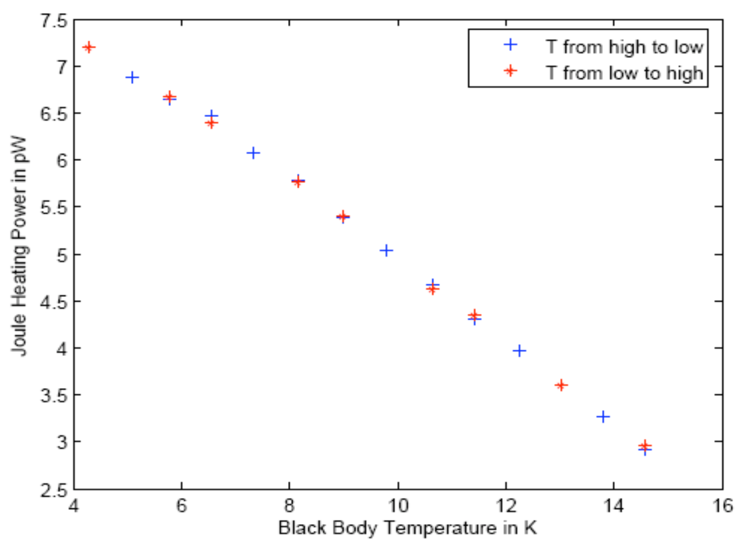
Prototype 100 GHz
single pol filtered device

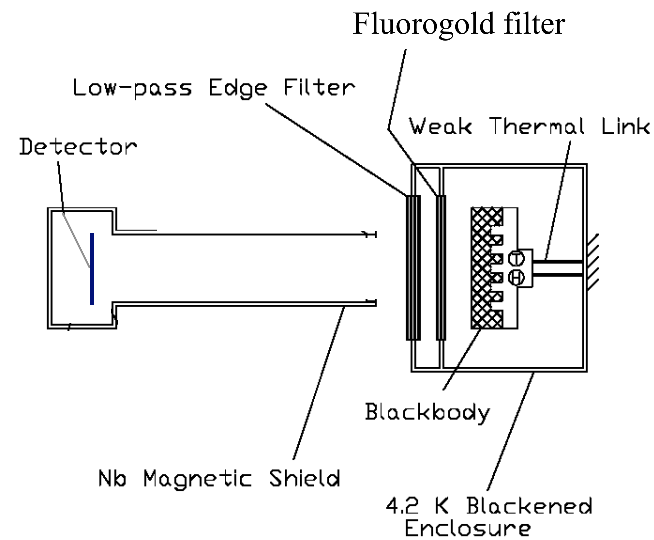




Optical Efficiency Test

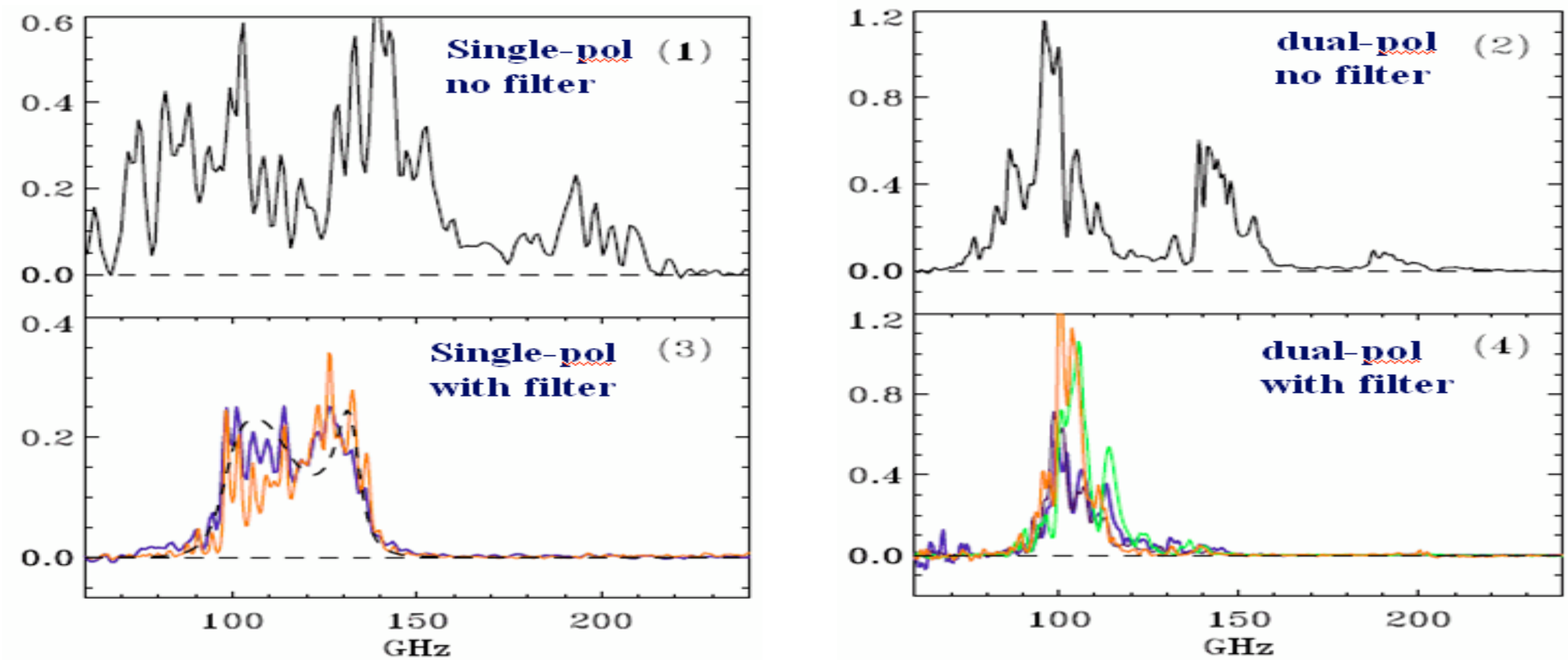






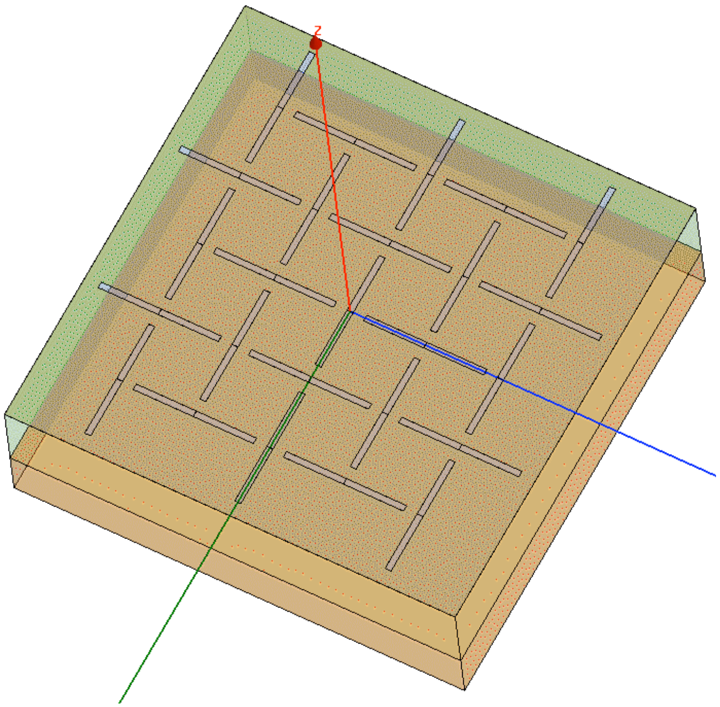
- Cold blackbody in Dewar
- 4K ~ 20K
- Slope is used to normalize the spectra
- G ~ 500 pW/K at 0.9 K

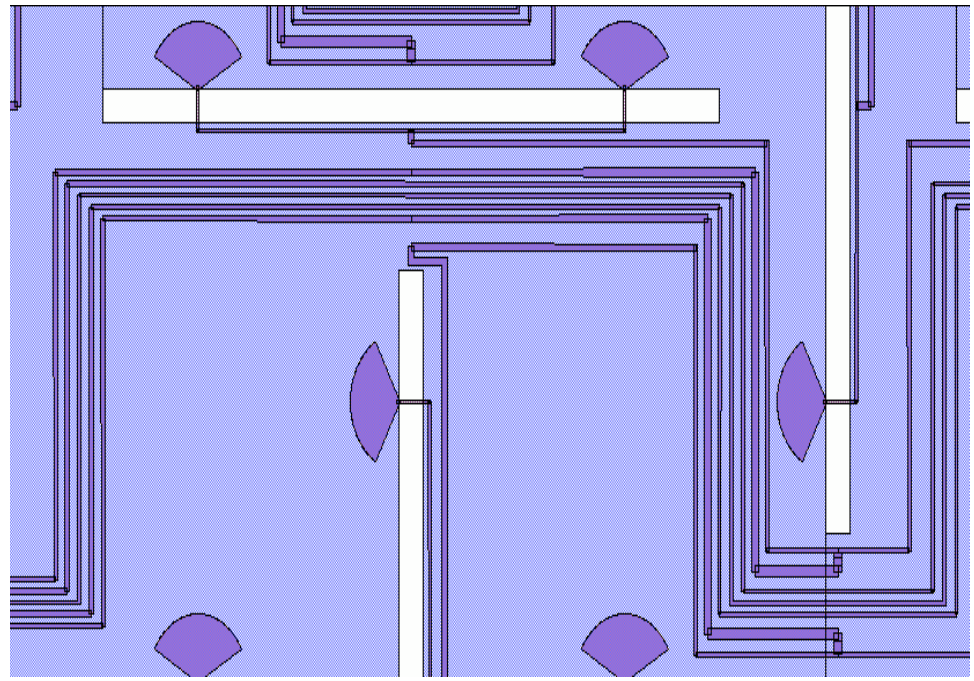
Spectra



- **Wide band single polarization antenna: low optical efficiency and fringes caused by feed network**
- **Dual polarization antenna has usable bandwidth ~ 20%; high optical efficiency**
- **The lumped element filters produce satisfying band ~ 30%, no leaks**

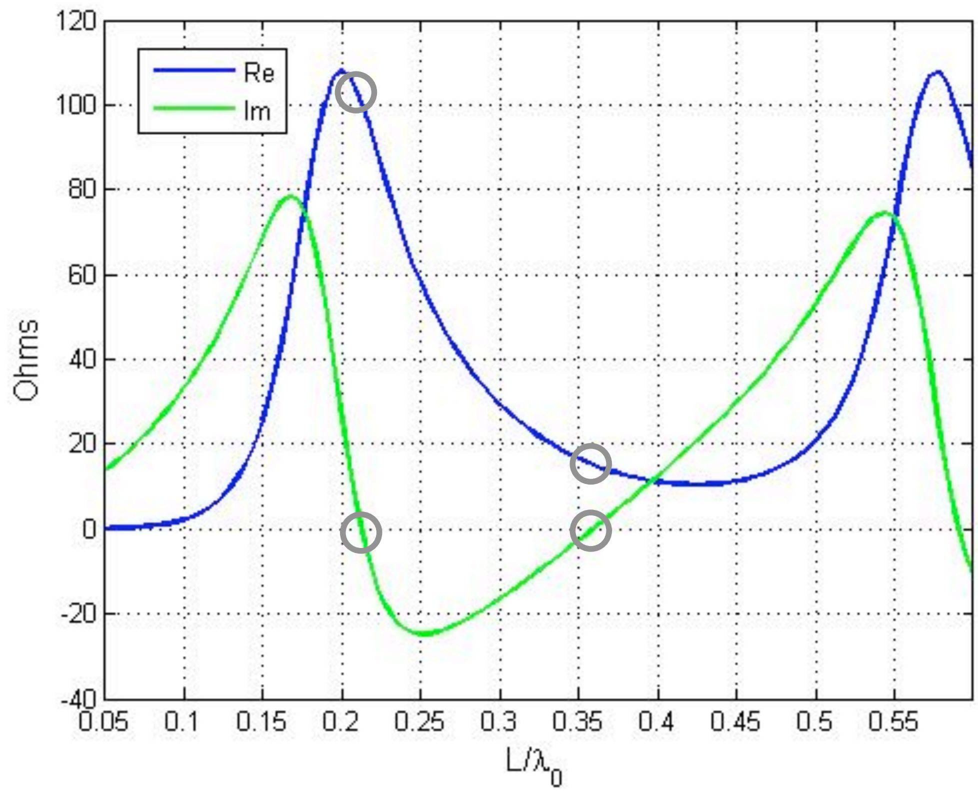
145 GHz Dual-Pol Antenna Array





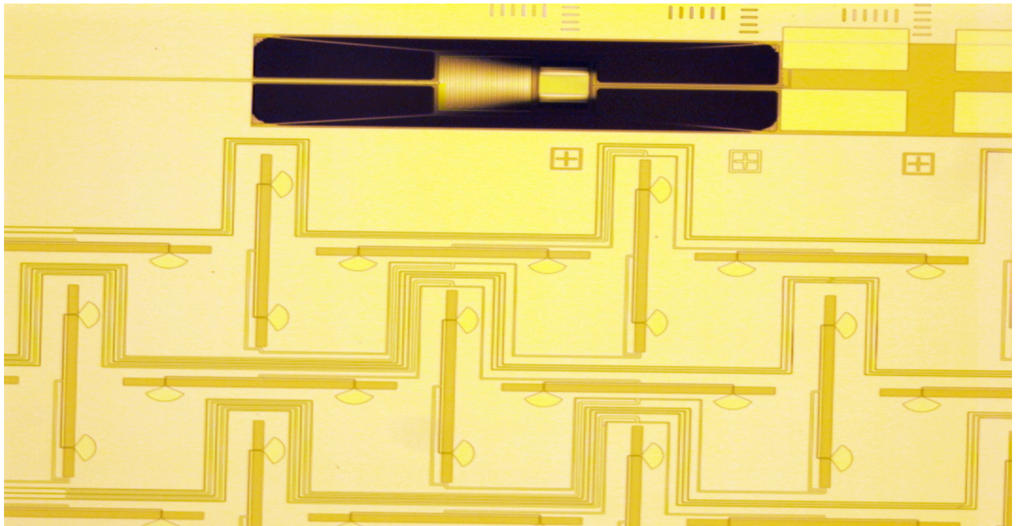
- New design with HFSS simulation (Goutam Chattopadhyay) and moment method calculation (Peter Day)
- Reduced cross polarization
- Increased band width
- High impedance (~ 40 Ω), Nb transition line is really narrow

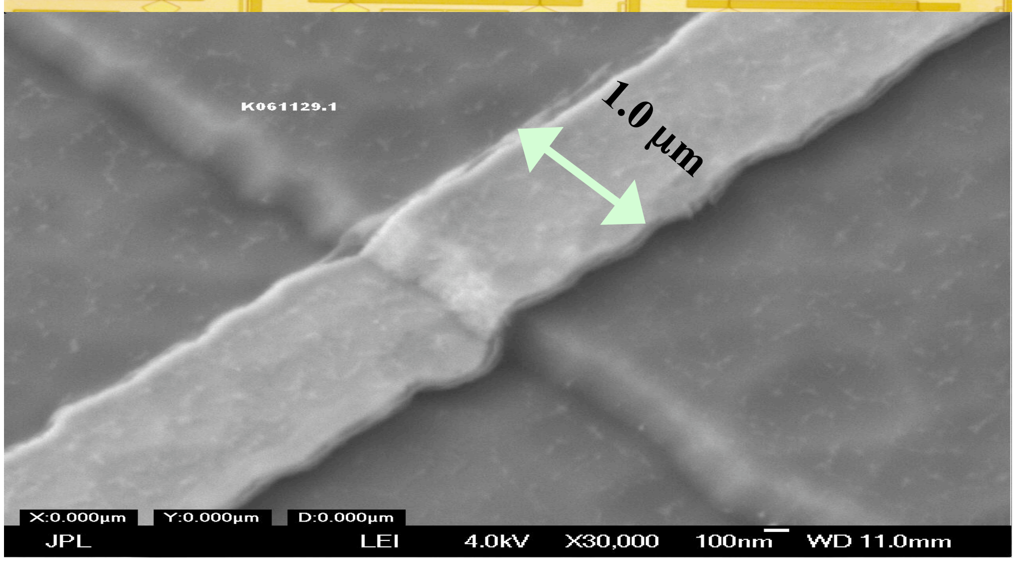
Antenna Impedance Plot



- At the resonance (Im Z = 0), the feed sees a simple resistive load
- The feed transmission line needs to match the impedance of this load
- Short slots are more compact, but could reduce transmission microstrip width to below 1μm due to high impedance of the slot antenna

New Dual-pol Antenna



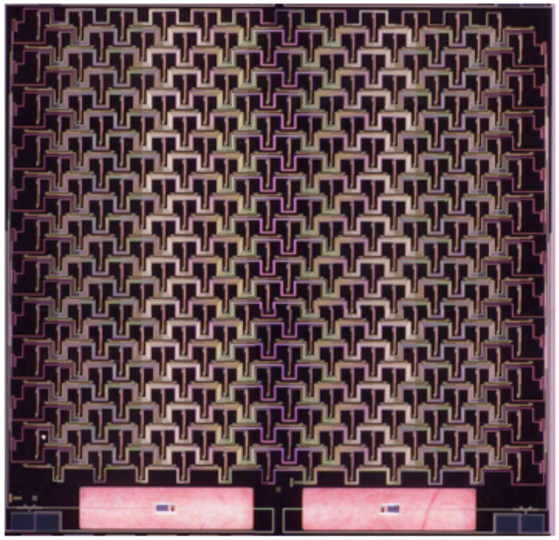


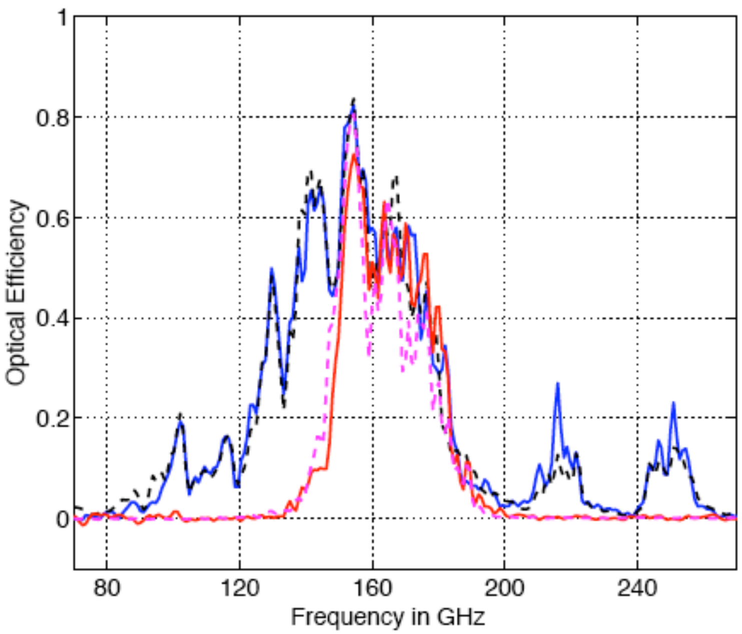
8 Layers:

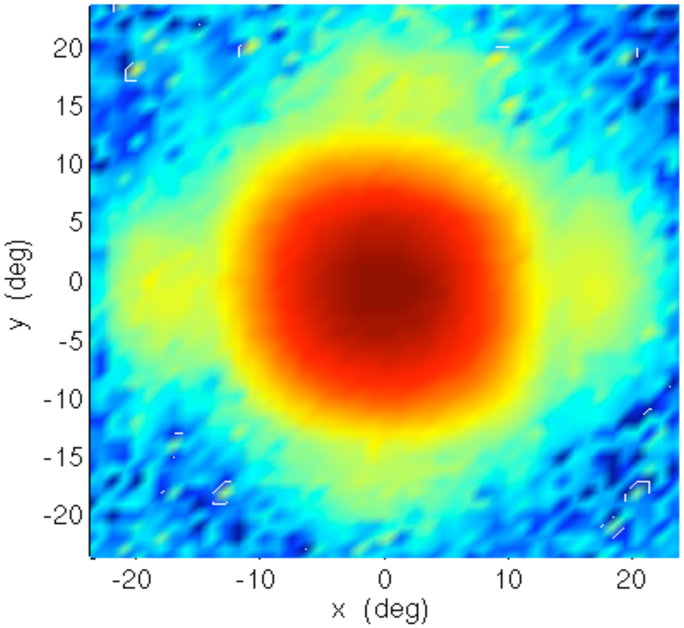
- Mo/Au-TES
- Protect
- Ground Plane
- ILD
- Resistor
- Resistor Protect
- Microstrip
- FSN

New Antenna – coupled TES

- Molybdenum gold bi-layer TES, Tc is between 450 mK and 500 mK
- Spectra without filters look good, band width is over 30%
- Filter's band pass is clean
- Optical efficiency is at 60% level
- Cross polarization < 2%
- Nice beam, ellipticity < 3%

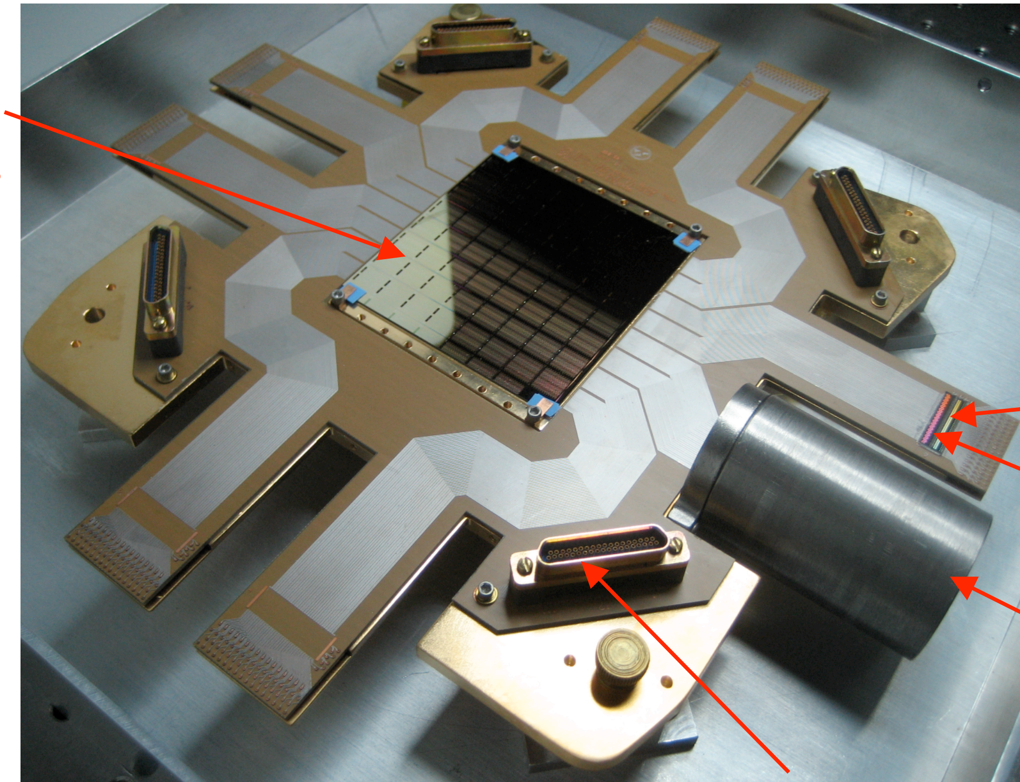






Single Tile Focal Plane for Array Test

Array location with
8x8 = 64 pixels
8x8x4 = 256 readouts



Nyquist chip

1st-stage
SQUID chip

Nb-shield

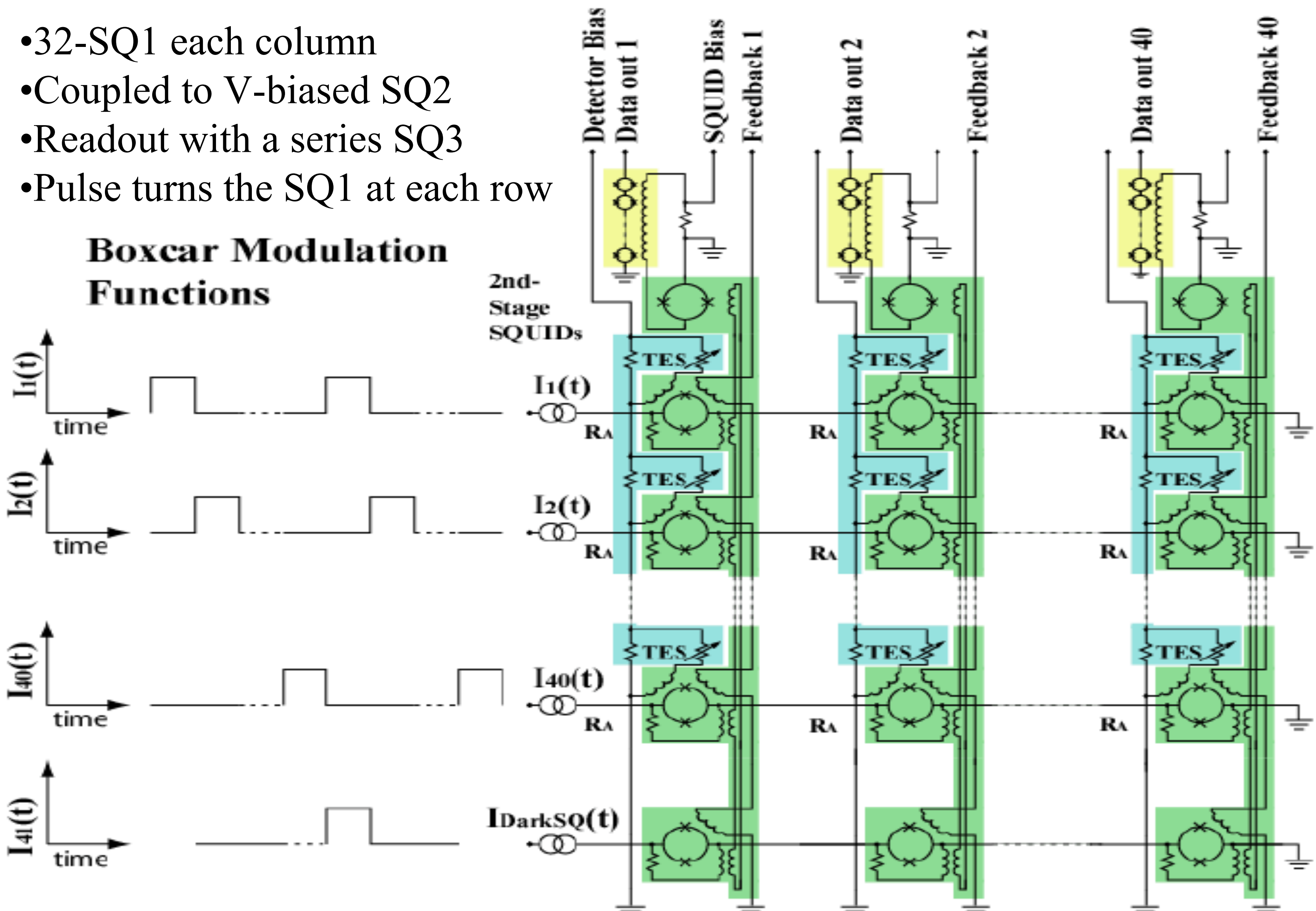
Connectors for
-Address lines
-Detector bias
-Output to 2nd-stage
SQUIDs

Lab test under the way at JPL,
limited by cryogenic issues

Time-Division Multiplexing

De Korte et al., NIST

- •32-SQ1 each column
- •Coupled to V-biased SQ2
- •Readout with a series SQ3
- •Pulse turns the SQ1 at each row

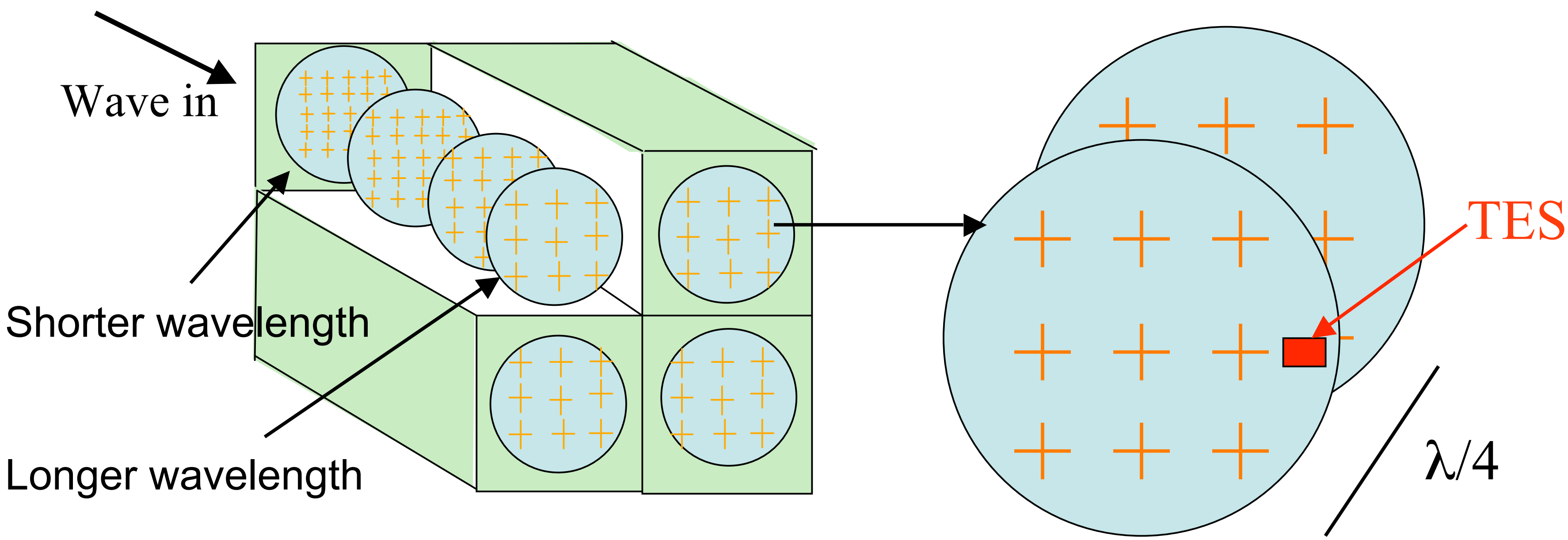


Excess noise control

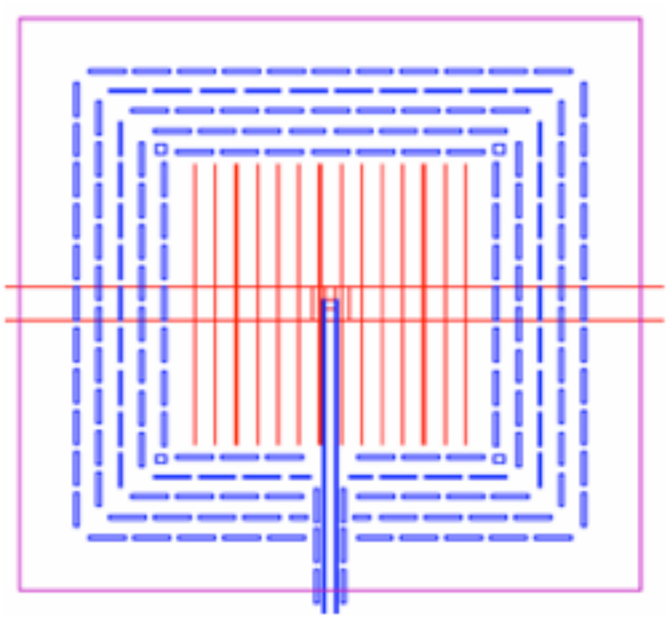
- Magnetic field could cause significant noise in TES and SQUID
  - Vortex motion in TES film
  - Trapped flux of DC field in SQUID
  - Trapped flux motion due to strayed AC field in SQUID
- Sources of field: Earth's field, waveplate motor, electronics, etc
- SQUID is very sensitive to magnetic field, to reach 1μKrts sensitivity, magnetic field need be controlled below 5nT
- Magnetic field effect in TES is about 1.5mK/Gauss, TES with voltage bias requires magnetic field below 1μT
- Multilayer magnetic shielding: cryoperm + niobium tube
- Excess noise appears at low bias of TES

Multicolor Frequency Selective TES array

- Part of SPEectral Energy Distribution (SPEED) project to study the spectral energy distribution of high red-shift galaxies. The star formation in the early universe
- 4 x 4 pixel array operating @ sub 0.5 K temperatures; each pixel is a frequency selective bolometers stack that enables sensing radiation at 150, 220, 270, 350GHz
- Simultaneous spatial and spectral measurements
- Efficient use of focal plane area



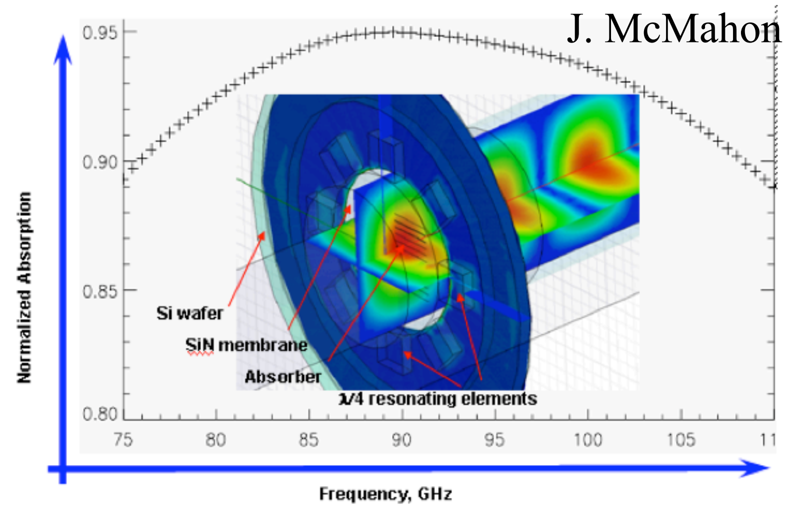
Absorber Type Polarimeter

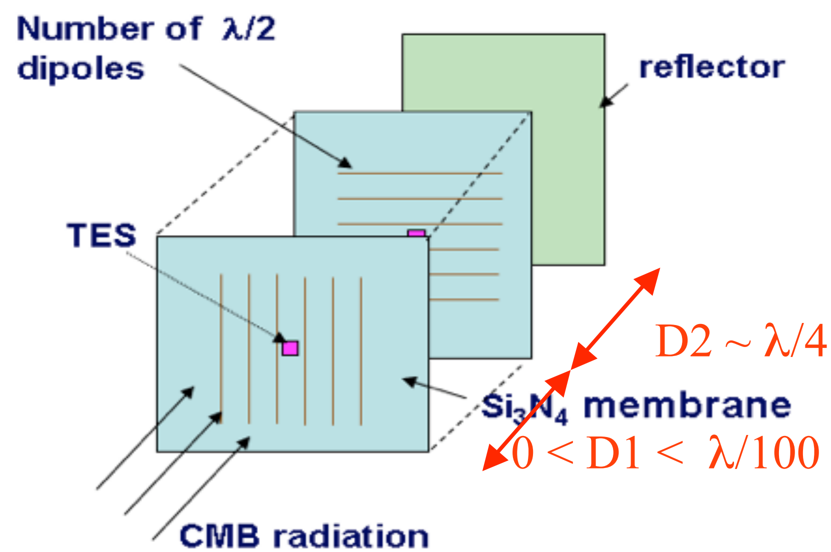


Simulation for 95GHz
14stripes, length 1.660mm, width 3μm , R=7Ω/sq

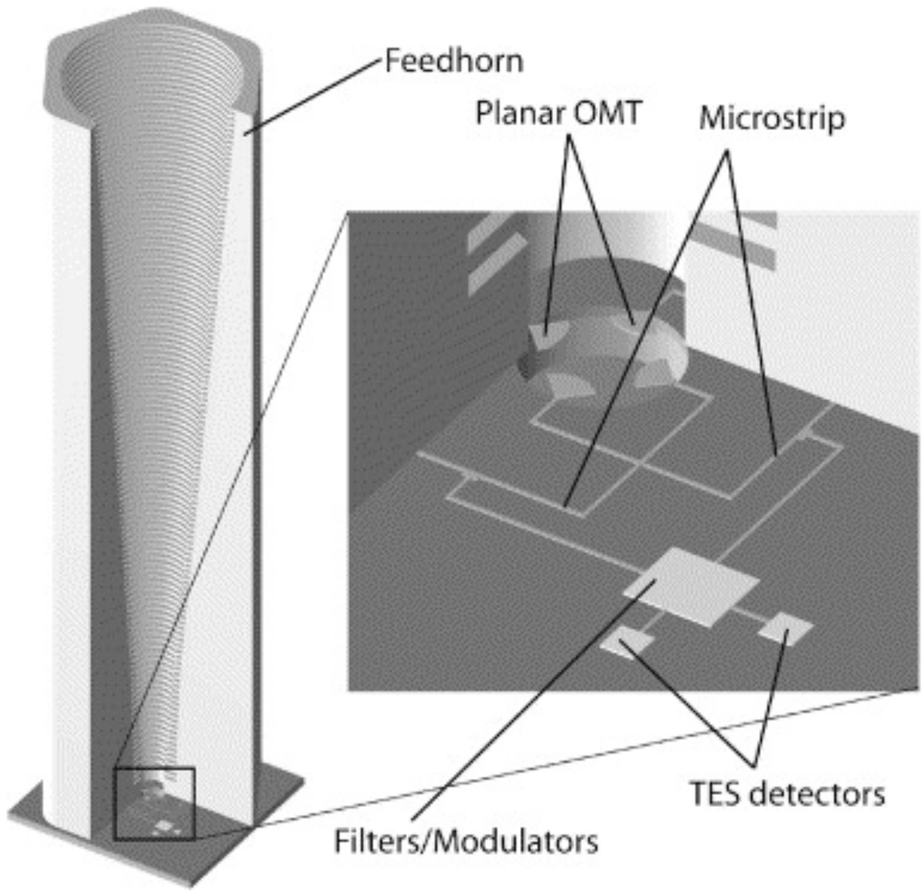
$$Z \approx R\frac{L}{W(N+1)}$$

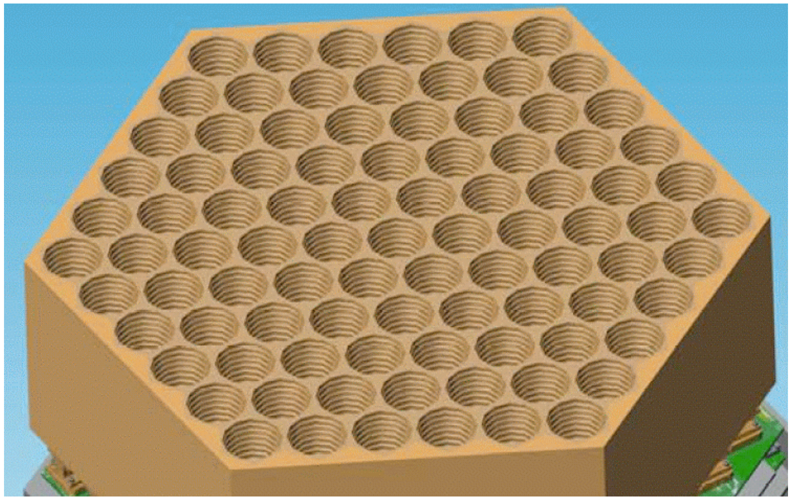
J. McMahon

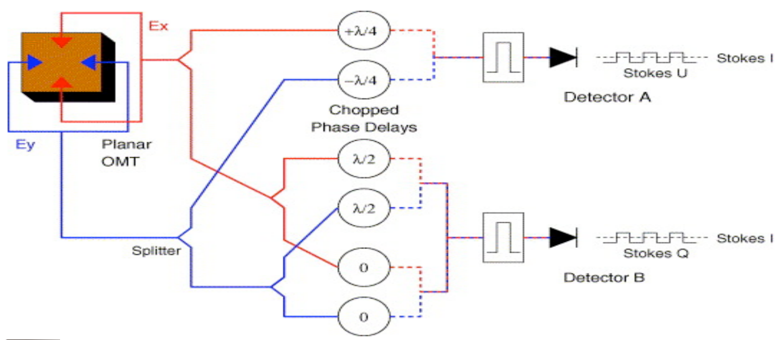


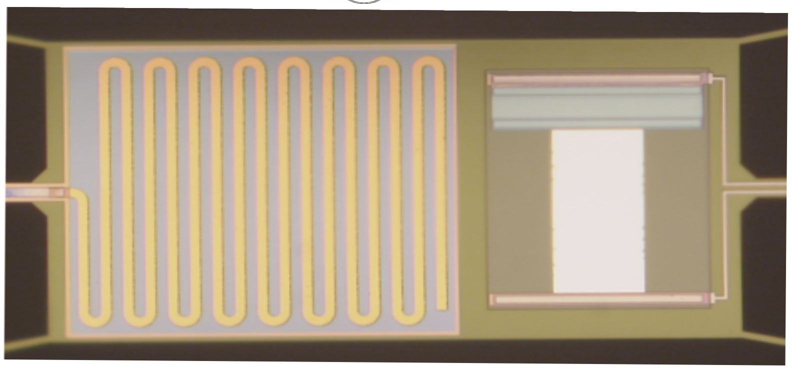


Integrated large array for Q/U measurements









PAPPA, Xpol < -45dB

Current Status and Future Plan at ANL

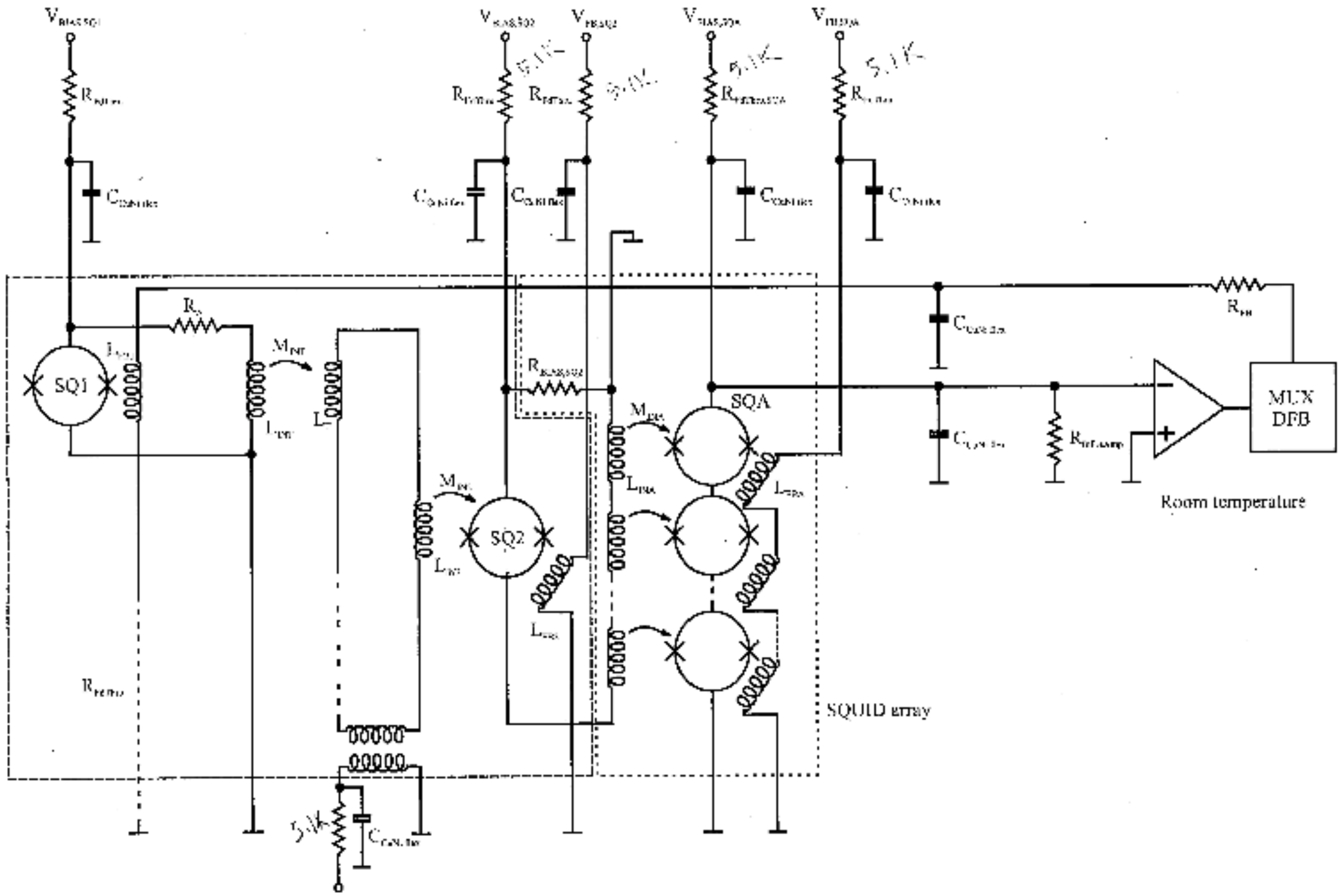
- Frequency selective bolometers for SPEED
  - Micro-fabrication of prototype array;
  - Dark and optical measurements, noise characterization;
  - Device assembling for ground telescope observation
- Polarimeters for SPT
  - Simulation and design (HFSS)
  - Thermal modeling and G tuning
  - Microfabrication of prototype devices
  - Dark and optical measurements
  - Noise characterization
  - Horn coupled large format polarimeters array (thousands of pixels) in polarization-sensitive measurements for the SPT observations
- Enhancing micro-fabrication capability
- SQUID-based multiplexing read-out for detectors array
- New applications, for example, X-ray dispersive fluorescence analysis

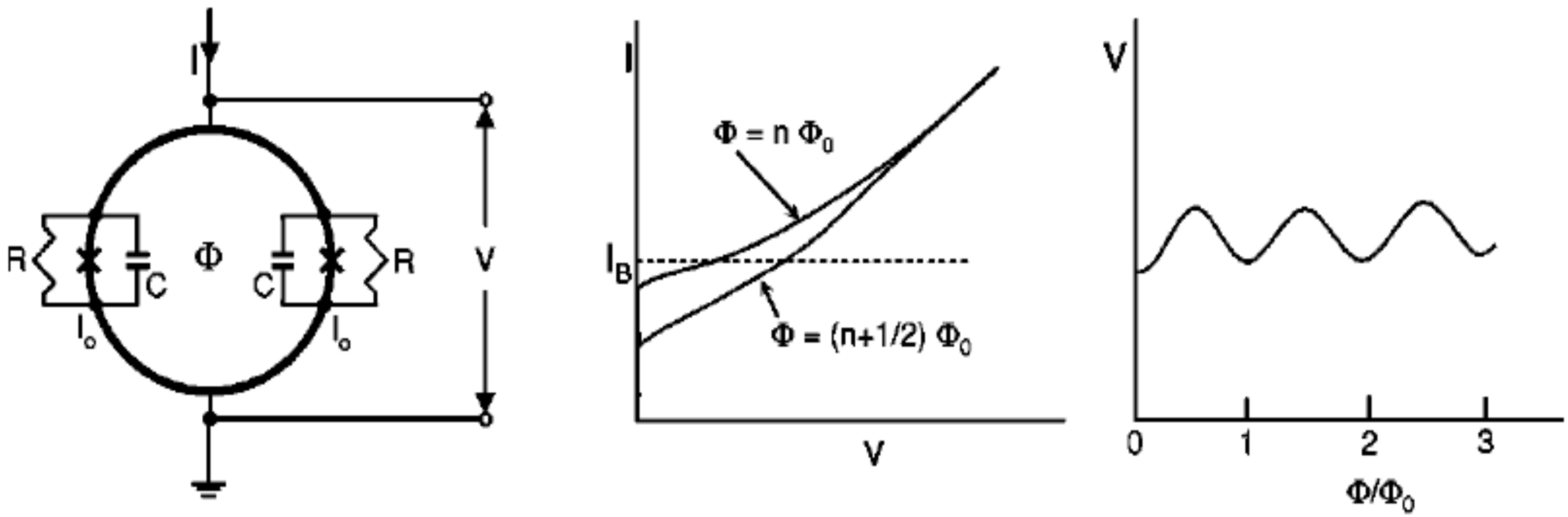
Summary

- Antenna-coupled TES bolometer technology has been demonstrated
- Large format arrays will instrument a balloon borne CMB experiment -- SPIDER, and an upgraded south pole CMB experiment (BICEP) -- SPUD
- Large format array technology is competitive for future space experiment – CMBpol
- Detector technology efforts at ANL, such as frequency selective bolometers and absorber type polarization sensitive bolometers

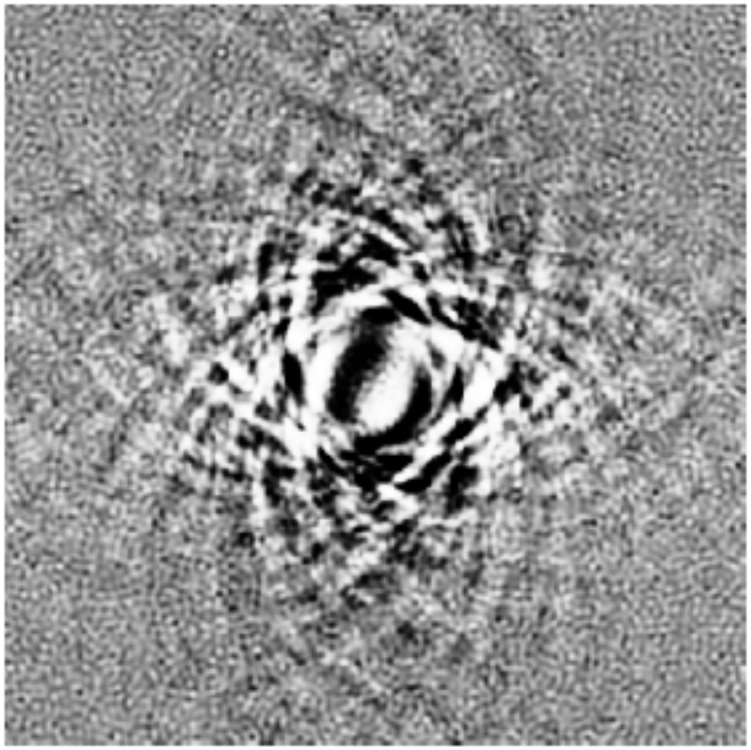
Acknowledgements

- Caltech J. Brevik, A. Goldin, S. Golwala, C. L. Kuo, A.E. Lange, P. Rossinot, A. Trangsrud, A. Vayonakis, G. Wang, J. Zmuidzinas
- JPL J.J. Bock, A. Bonetti, G. Chattopadhyay, P. Day, W. Holmes, M. Kenyon, R. LeDuc, J. Stern, A. Turner, M. Yun
- NIST W. Doriese, G. Hilton, K. Irwin, C. Reintsema
- ANL A. Datesman, R. Divan, V. Novosad, J. Pearson, G. Wang, V. Yefremenko
- U of C J. E. Carlstrom, C. Cheng, T. Downes, J. McMahon, S. S. Meyer


SQ1
SQ2
SQA
MUX
DFB
Room temperature
SQUID array
5.1K
5.1K
5.1K
5.1K
5.1K


I
R
C
Φ
C
R
I_o
I_o
V
I
$\Phi = n\,\Phi_0$
I_B
$\Phi = (n+1/2)\,\Phi_0$
V
V
0
1
2
3
Φ/Φ_0

B-mode Lensing



W. Hu and T. Okamoto, ApJ 2002

$$NEP_{BLIP} = \sqrt{\sum \left[2P_i \left(h\bar{\nu} + \varepsilon_i \eta_i k_B T_i \right) \right]}$$

The first term is the contribution from photon random arrivals (shot noise due to Poisson statistics). The second term accounts for the effect of photon correlation and depends on the source emissivity and temperature, and the net efficiency through the optics to the detector

$$A = \left(\frac{4n}{(n+1)^2} \right) \frac{4nZ_0R_0}{\left((n+1)R_0 + Z_0 \right)^2}$$