A short review of select technologies for readout of low-temperature detectors: Paramps, KPUPs, and the Microwave SQUID mux

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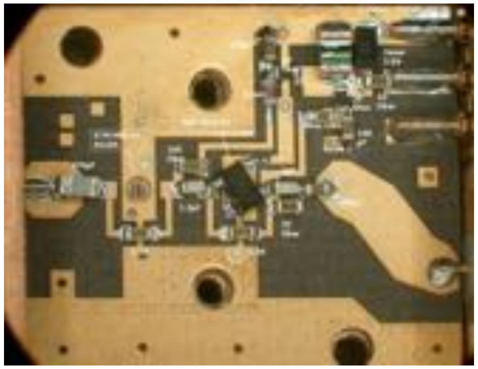
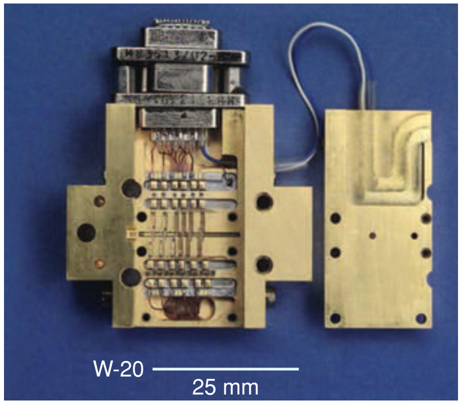
Some context first:
Semiconducting low-noise amplifiers

Transistor-based cryogenic amplifiers for
low-temperature measurements:

InP HFET (HEMT), SiGe bipolar



0.5-4 GHz SiGe, Weinreb (Caltech)



W-band MAP amplifier

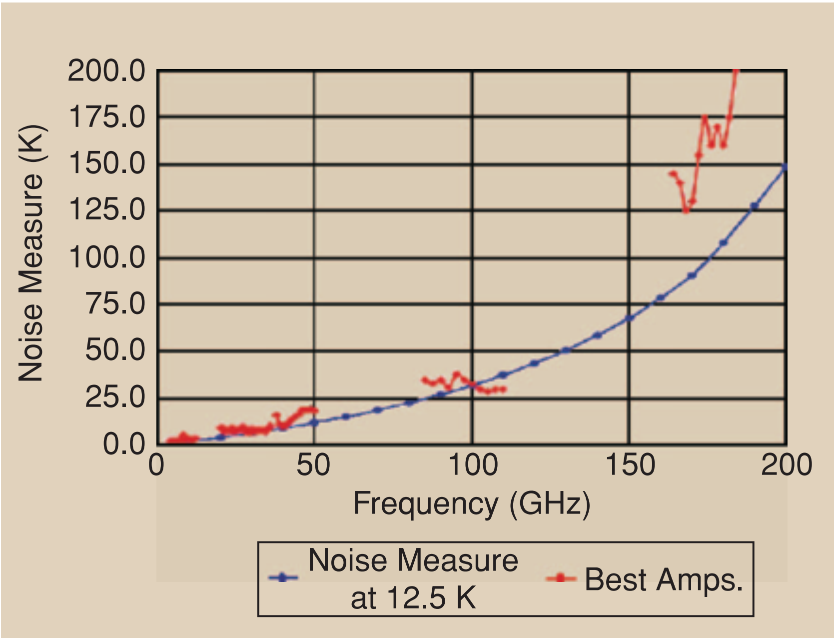
The good:

- Broad frequency band
- High dynamic range (~ -45 dBm for LNF 4-8 GHz) (good for readout of ~ 1000 MKID pixels)
- High gain (30-40 dB)
- Suitable for readout of multiplexed detector arrays (for imaging or spectroscopy)

The not-so-good:

- Noise limited to $\gtrsim 5 \times h\upsilon/k = 2.5$ K (@10 GHz)
- Moderate power dissipation (~ 5-10 mW)
- Not compatible for integration with superconducting electronics
- **Main noise limiting component in most detector readout systems.**

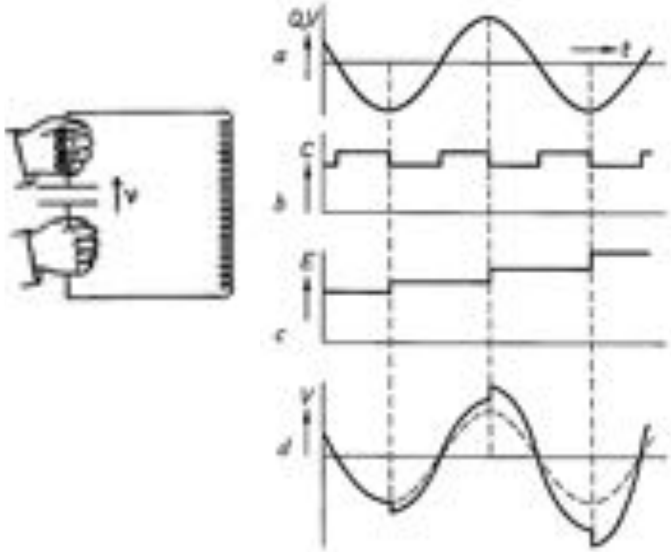
State of the art for InP HFETs



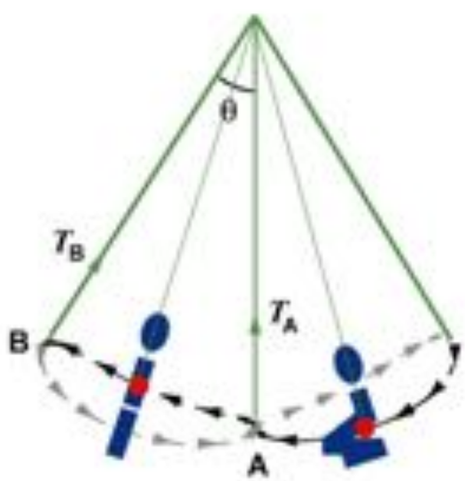
M. Popieszalski, IEEE microwave magazine, 2005

Parametric Amplification

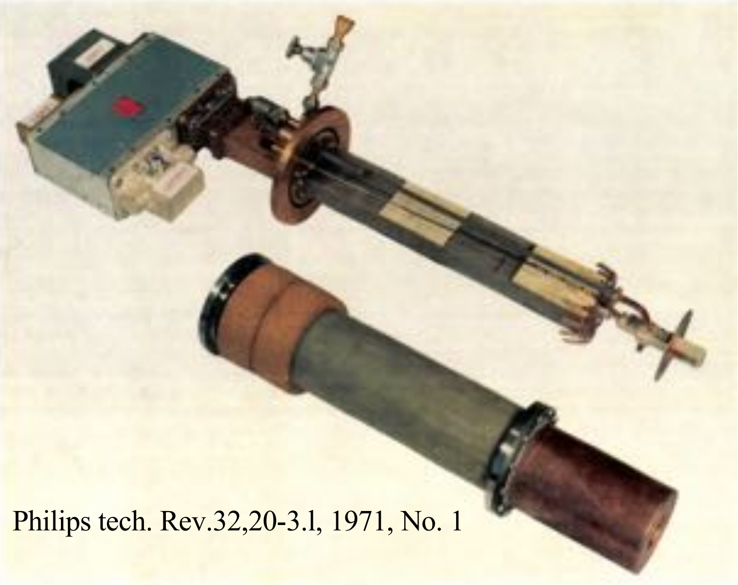
Time-varying capacitor or inductor
(at twice the signal frequency)



A child swing is a mechanical analog.



Example: A LN2-cooled varactor-diode paramp for the 2.7 GHz radio interferometer at Defford, England (1971)

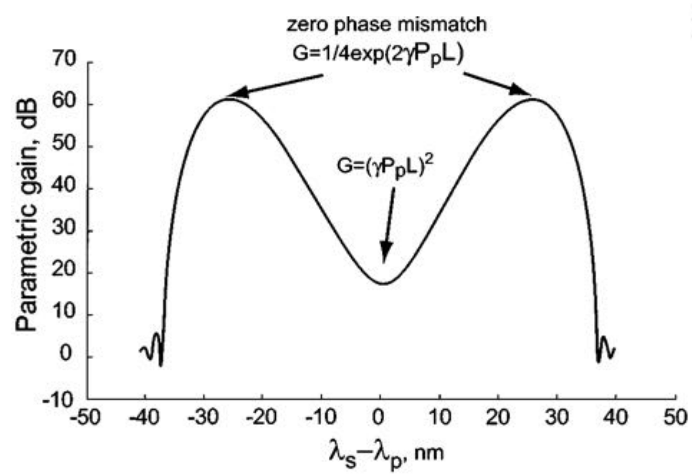


Philips tech. Rev.32,20-3.l, 1971, No. 1

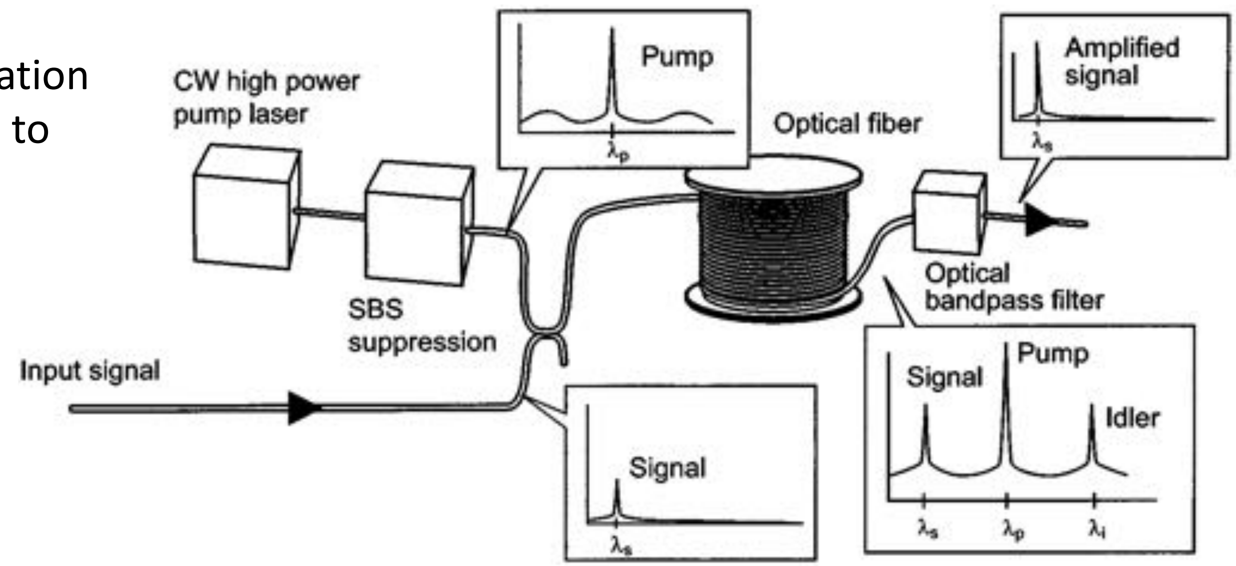
- Power is transferred from a strong pump tone to a weak signal by exploiting an inductive or capacitive nonlinearity and the mixing process.
- Amplification is ideally is a noiseless process (if no loss in device) except for an added ½ photon noise resulting from of the the vacuum fluctuations leaking in from the image sideband.

Analog: optical fiber-based parametric amplifier

- "Kerr medium" in fiber produced from intensity dependent refractive index
- Nonlinearity leads to amplification
- Idler tone is produced
- $\omega_p = \omega_s + \omega_i$ or $2\omega_p = \omega_s + \omega_i$
- Phase matching is required
- Widely used in optical communication
- Purely reactive nonlinearity leads to Quantum-limited
- Large gain (60 dB)



Hansryd, IEEE Quantum Electronics, 2002

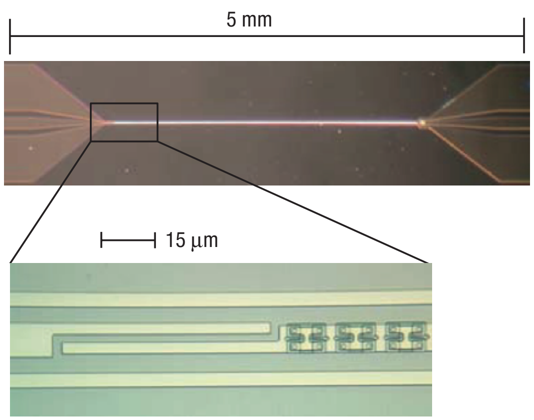


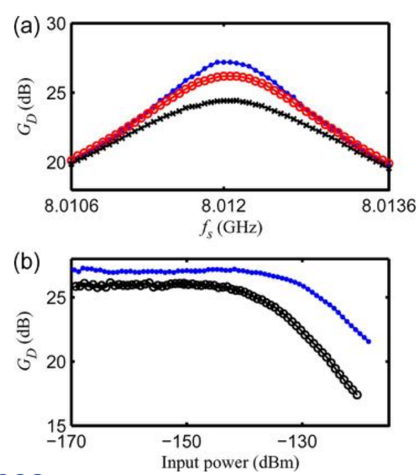
Josephson-junction-based paramps: resonant vs non-resonant versions

<u>Resonant:</u> Kerr medium made of 480 SQUIDs in series embedded in a microwave cavity

<u>The good:</u>
- Purely reactive non-linearity → Quantum-limited noise (noise temperature at QL = hυ/k ~ 0.5 K @10 GHz
- Very low dissipation, Integration with superconducting electronics

<u>The not-so-good:</u>
- Very small instantaneous bandwidth (~< 10 MHz)
- Fixed gain-bandwidth product
- Very small dynamic range (<-100 dBm) -> readout of at best few photon detectors
- Requires < 100 mK operation (15 mK here)
- Limited to multiplexed readout of only a few photon detectors



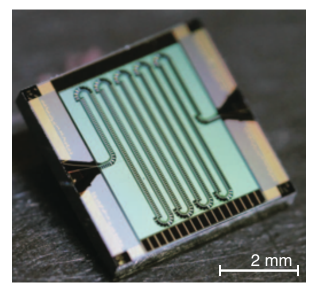


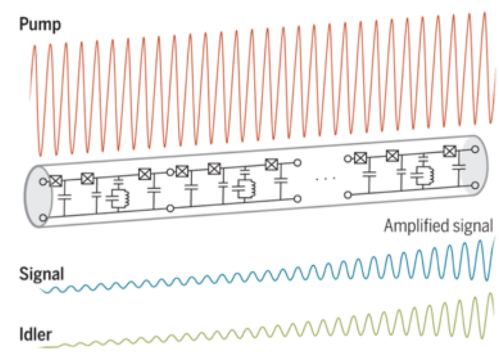
K. Lehnert (JILA/NIST)
M. Castellanos, Nature Physics, Vol 4, 2008

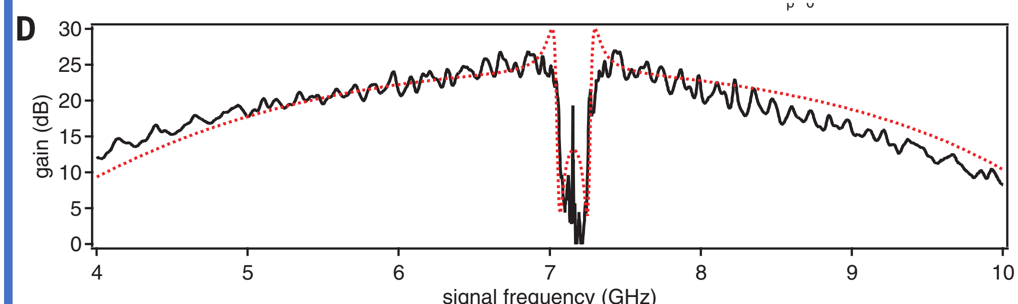
<u>Non-Resonant:</u> Kerr medium made of 2000 SQUIDs in series embedded in a low-loss transmission-line

<u>The good:</u>
- Noise approaching the QL (~ x2)
- Several GHz bandwidth
- Very low dissipation, Integration with superconducting electronics

<u>The not-so-good:</u>
- Very small dynamic range (<-90 dBm)
- Requires < 100 mK operation (35 mK here)
- Limited to multiplexed readout of only a few photon detectors







C. Macklin, Science, 350 (6258), 2015

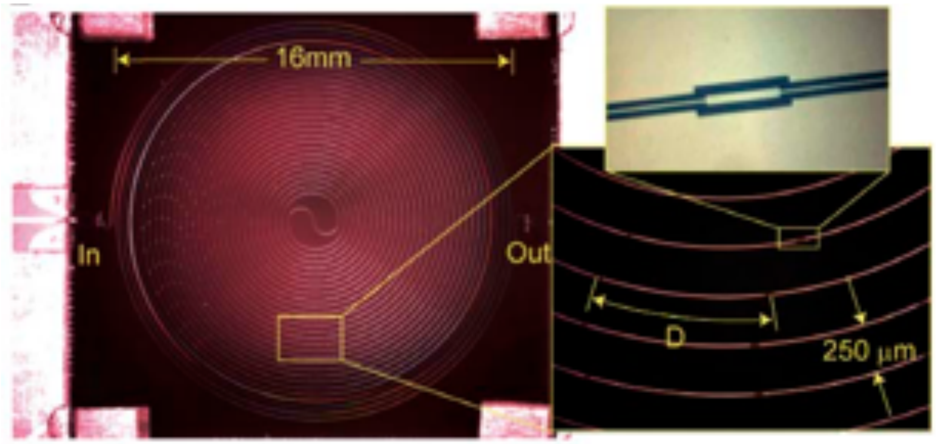
Traveling-wave Kinetic Inductance Parametric Amplifier

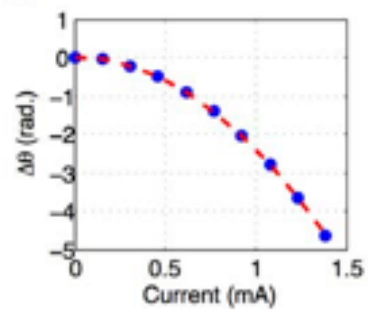
nature physics ARTICLES
PUBLISHED ONLINE: 8 JULY 2012 | DOI: 10.1038/NPHYS2356

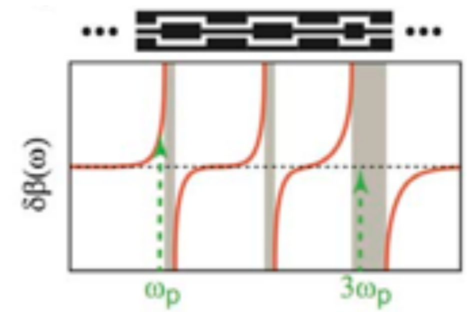
A wideband, low-noise superconducting amplifier with high dynamic range

Byeong Ho Eom[1], Peter K. Day[2]*, Henry G. LeDuc[2] and Jonas Zmuidzinas[1,2]

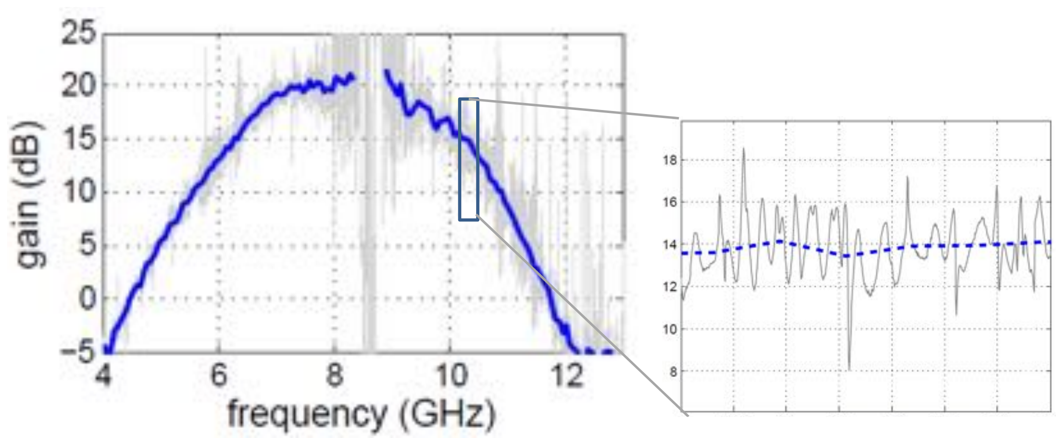
- Invented by Zmuidzinas et al. at Caltech/JPL circa 2011
- Kerr medium made of ultra low-loss and high kinetic inductance film (e.g. NbTiN) in a transmission-line arcitecture
- Nonlinearity: $\delta L_{kin} \propto I^2$
- Spin-off from ultra-high-Q TiN KID work at Caltech/JPL







The good:
- Quantum-limited noise demonstrated
- Octave or more bandwidth
- High dynamic range (~ -50 to -45 dBm) demonstrated
- Very low dissipation
- Can operate at up to ~ 4K
- Integration with superconducting electronics
- Can read out large array of detectors



The not-so-good:
- High pump power (100 µW in 1st generation)
- Large ripple (1st generation)
- Long length of 80 cm (1st generation)

B. Eom, Nature Physics 8, 623–627 (2012)

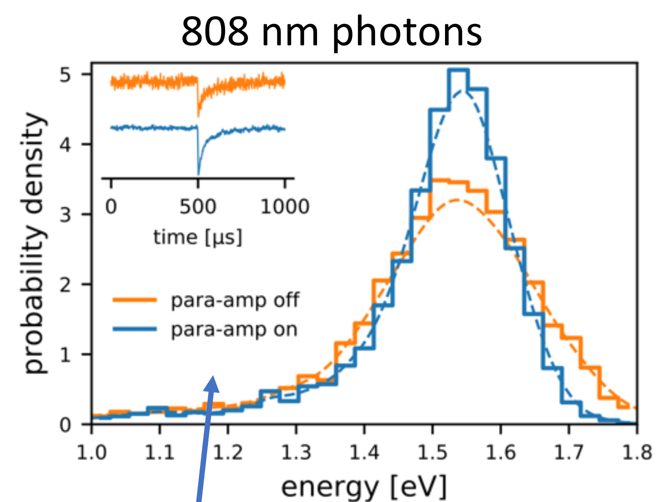
Application example for paramps:

Wide-band parametric amplifier readout and resolution of optical microwave kinetic inductance detectors

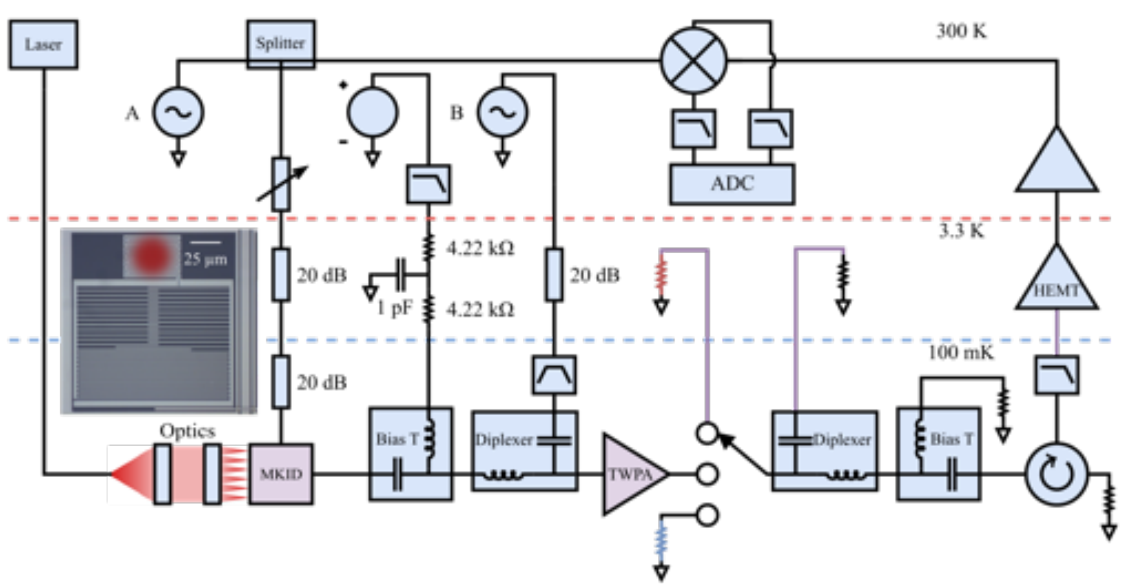
Nicholas Zobrist,[1,a)] Byeong Ho Eom,[2] Peter Day,[2] Benjamin A. Mazin,[1,b)] Seth R. Meeker,[2] Bruce Bumble,[2] Henry G. LeDuc,[2] Grégoire Coiffard,[1] Paul Szypryt,[3] Neelay Fruitwala,[1] Isabel Lipartito,[1] and Clint Bockstiegel[1]

Appl. Phys. Lett. **115**, 042601 (2019)

- Application in exoplanet imaging coronographs: Single-photon energy-resolving optical MKID arrays serve as multi-band wavefront sensors in adaptive optics for high-speed star-light speckle suppression.
- Example: MEC (MKID Exoplanet Camera): ~ 20,000 PtSi MKIDs (800-1300 nm)
- Energy resolution (measured with paramp) R ~ 10
- R is currently limited by MKID design (current non-uniformity in absorber, TLS noise) and hot phonon escape to substrate. Could be improved to ~ 25.
- Talk by N. Zorbist (Friday)



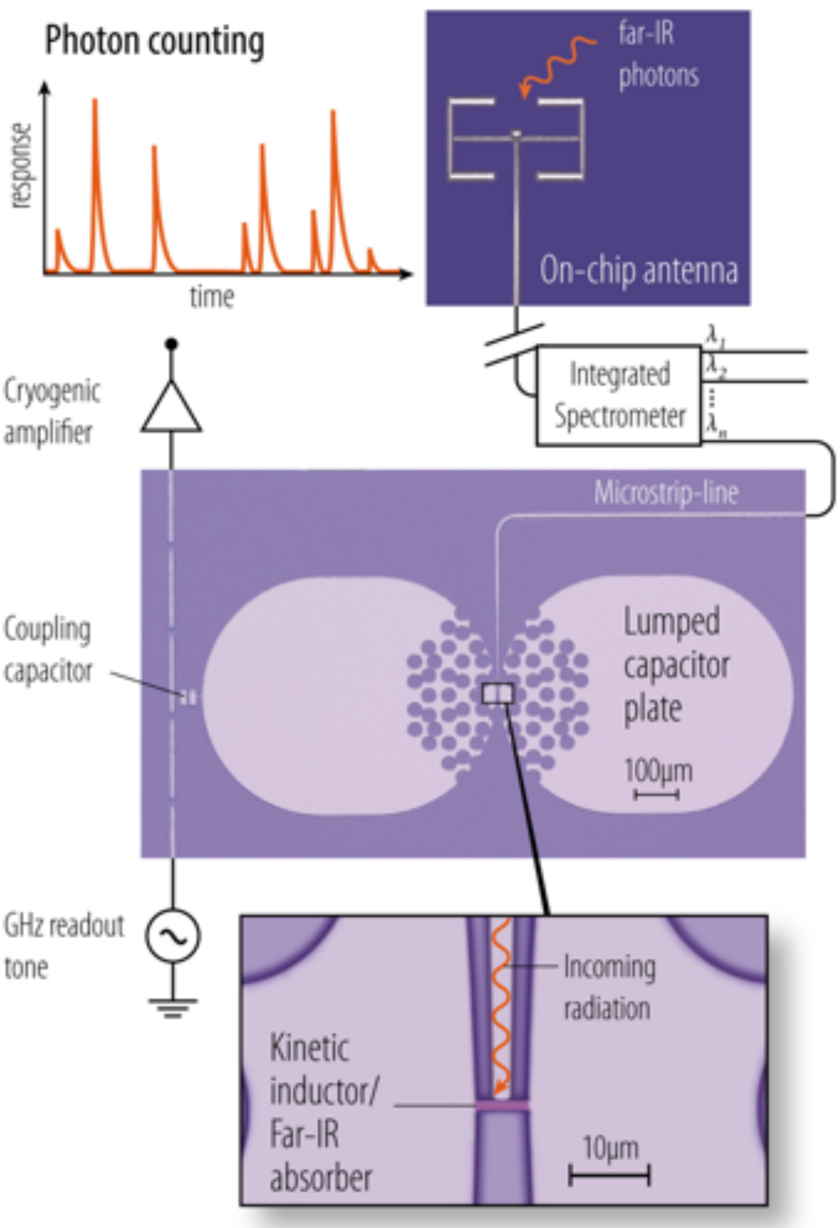
A_I	A_P	A_H	A_{sys}
$0.71^{+0.03+0.2}_{-0.03-0.01}$	$0.59^{+0.02+0.2}_{-0.02-0.07}$	$19.5^{+0.1+2}_{-0.1-2}$	$2.13^{+0.01+0.8}_{-0.01-0.1}$



	Resolving Power ($E/\Delta E$)	
Energy (eV)	Measured	Expected
1.53 (808 nm)	5.8 → 8.9	9.5 → 23
1.35 (920 nm)	7.4 → 9.4	10 → 24
1.27 (980 nm)	7.5 → 9.6	11 → 25
1.11 (1120 nm)	6.6 → 9.6	9.3 → 24
0.946 (1310 nm)	6.0 → 9.2	8.7 → 23

Application example for paramps:

Photon Counting with KIDs at THz/Submillimeter (NASA GSFC)

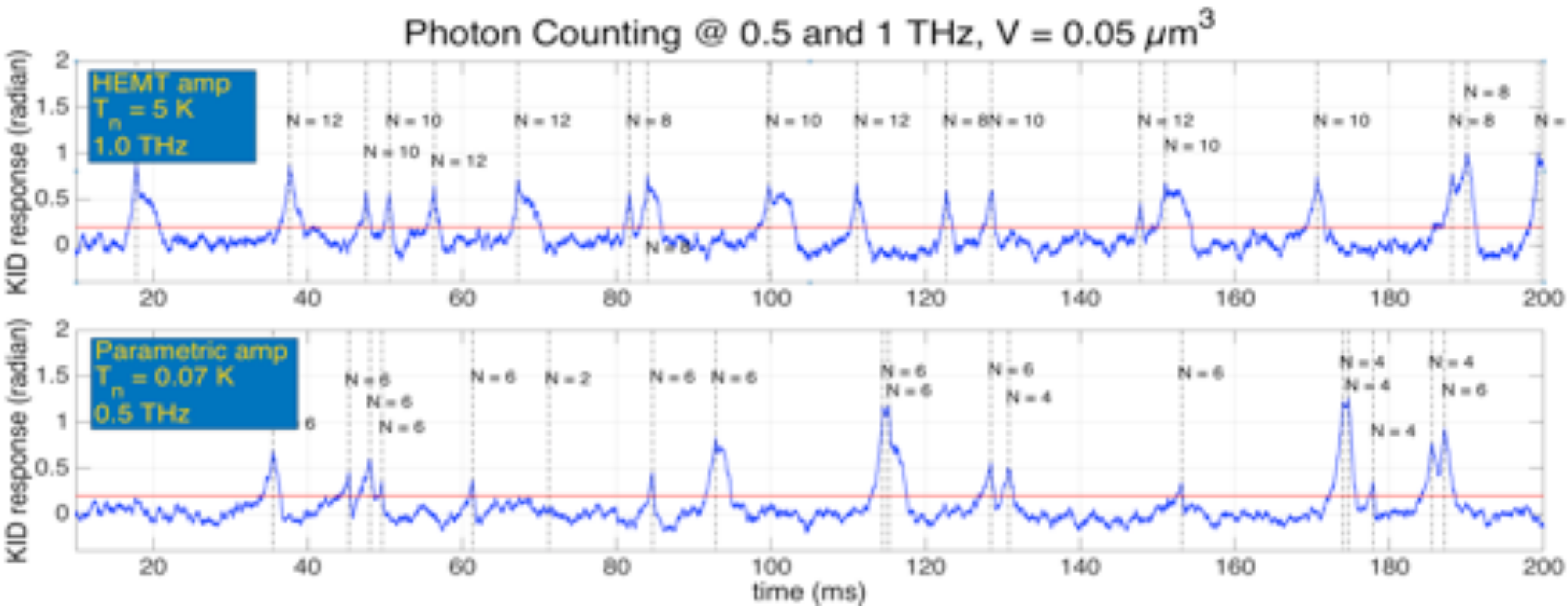


Motivation:
In space, when using R = 1000 spectrometer, background photon rate is: $10^2 - 10^4$ photons/sec, so potentially can do photon counting with KIDs

<u>Key design aspects:</u>

- Ultra-small volume aluminum kinetic inductor for increased response to single photons
- SOI wafer (currently 0.45 µm Si substrate)
- Parallel-plate capacitor on single-crystal Si for integration with on-chip spectrometer (µ-Spec) and reduced TLS frequency noise
- Choke filter for confinement of submm radiation inside sensitive inductor
- All-microstripline elements and no cuts in ground plane -> Immunity to stray radiation

Photon counting with KIDs in 0.5 -1.0 THz range with and without a paramp



- Dark count rate dominated by amplifier noise is 5 Hz. This corresponds to **NEP = 1-2 x 10^{-21} W/rt Hz in the 0.5-1 THz range** .
- Integrated over the signal bandwidth, TLS noise is sub-dominant to amplifier white noise, because internal Q is low during pulse. ✓
- Recombination time and ring time are fast compared to photon arrival rate. Pulses decay with tau ~ 1.7 ms. ✓
- **Counting photons with > 95% efficiency!**

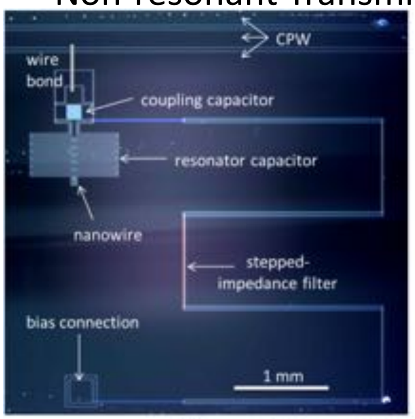
Assumptions:
photon rate = 100/s, spectrometer resolution = 1000, optical coupling efficiency = 25%, 4K telescope (conditions for high-Z galaxy case)
detector volume = 0.05 μm^3, bath temperature = 100 mK, readout power = -137 and -156 dBm
Material properties take from our films measured at GSFC.

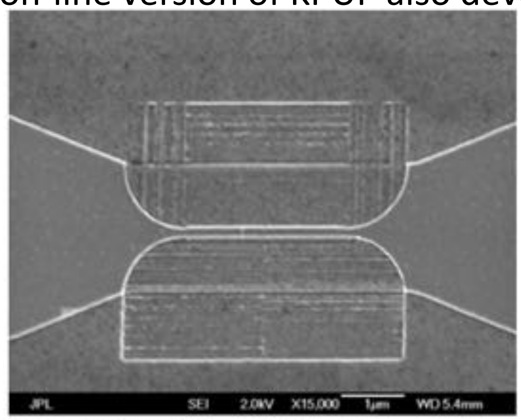
Kinetic Inductance Parametric Up-Converter

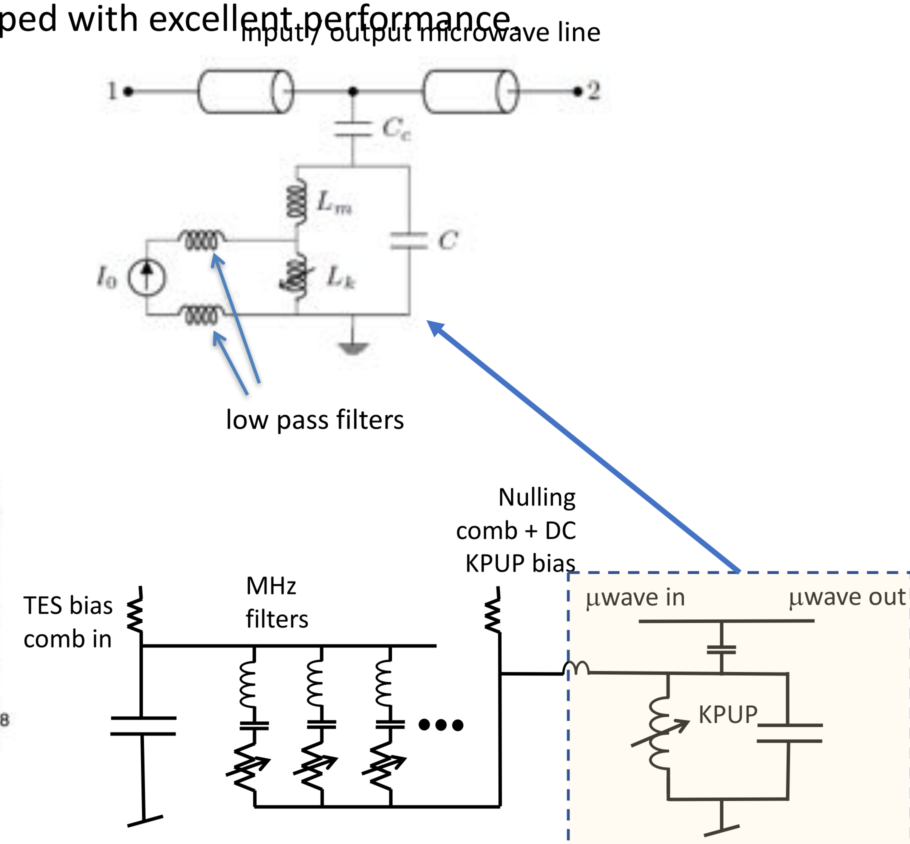
A. Kher[1] · P. K. Day[2] · B. H. Eom[1] ·
J. Zmuidzinas[1] · H. G. Leduc[2]

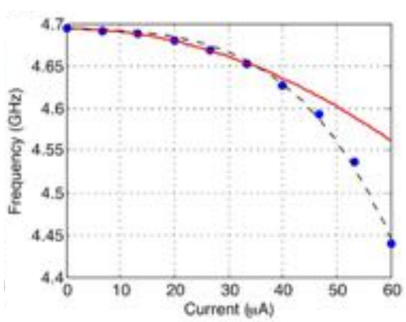
J Low Temp Phys (2016) 184:480–485
DOI 10.1007/s10909-015-1364-0

- KPUP is a current-sensitive resonator that can be multiplexed for detector readout (e.g. FDM-type TES readout)
- TiN nanowire inductor (170 nm x 2.6 µm x 10 nm) embedded in microwave resonator provides quadratic nonlinearity.
- A low-frequency (MHz) signal modulates the inductance and upconverts the signal to the GHz range.
- Many tones within the resonance bandwidth (~ 5 - 100 MHz) can be simultaneously upconverted and read out.
- One KPUP can be used to read out an array (~100) of bolometers or calorimeters (e.g. TES or MMC).
- Many KPUPs can then be multiplexed in frequency as a 2nd stage of multiplexing (Similar to KIDs) → Kilo-pixel arrays.
- Readout noise of KPUP is very small (10 - 30 pA/rt Hz) → suitable for very sensitive detector readout.
- Non-resonant Transmission-line version of KPUP also developed with excellent performance

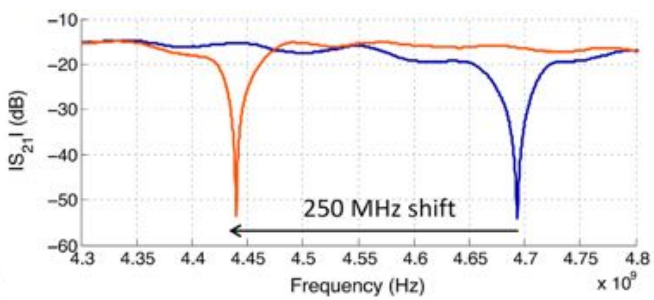








Frequency shift vs bias



Frequency shift at 60 µA of bias (5% change)

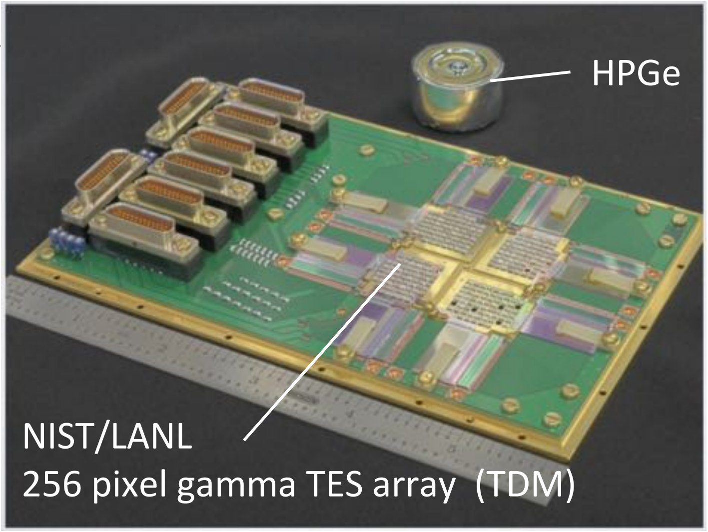
Many other applications of paramps and the kinetic inductance nonlinearity in the context of readout

- Application for space-based detector readout. e.g. for the Origins Space Telescope to read out arrays of photon-counting spectrometers
- Replacing high power consuming HEMT amplifiers with TKIPs for reducing SWAP in space platforms. (much less dynamic range needed compared to ground-based)
- Sensitive current sensors for multiplexed readout of large detector arrays (e.g. TESs) for astronomical telescopes (e.g. CMB-S4 needs ~ 10^5 TES or KID detectors)
- X-ray/Gamma-ray spectrometers for fast/real-time materials analysis in industry or national security.
- Deep-space communication – e.g. IF amplifiers for DSN
- Quantum Computing: readout of qubits in quantum processors
- Circuit QED experiments for fundamental physics

Short review of the microwave SQUID multiplexer (μMux)

Overall goal: Fast access to signals from large-format arrays with $10^3 – 10^6$ pixels

Applications: Precise measurement of the energy of individual photons,
X-ray spectrometer for NASA's Lynx space mission concept, Nuclear assay of materials, beam-line materials analysis



D. Bennett et al., *RSI* **83**, 093113 (2012)

Typical readout approaches for detector arrays:

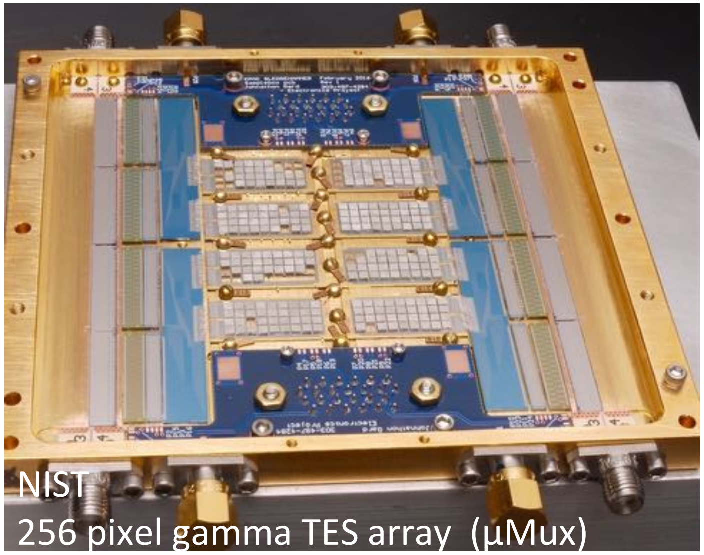
- Time-domain, Frequency-domain, Code-domain
  e.g. NIST/LANL 256 pixel TES spectrometer (TDM)

Disadvantages of above readout technologies:

- Limited to ~ 10-20 MHz readout bandwidth
- Large number of cryogenic wires
- System complexity

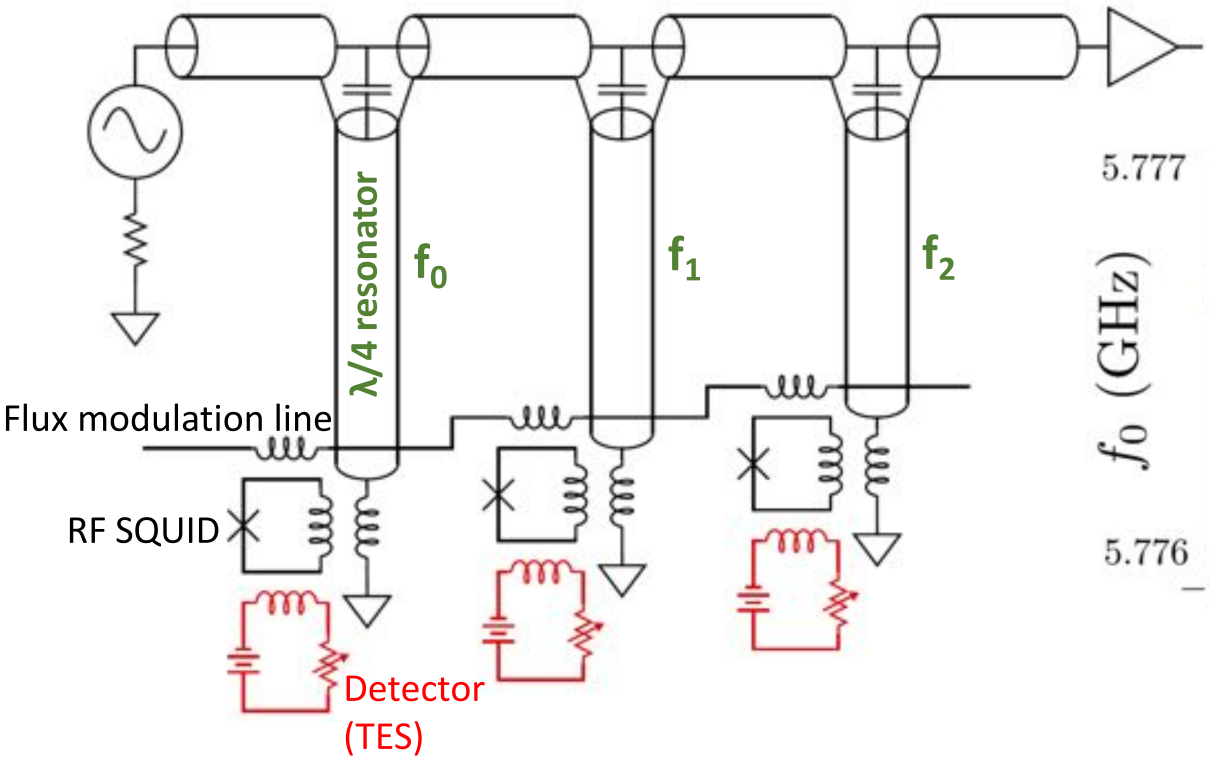
Advantages of the μ-Mux:

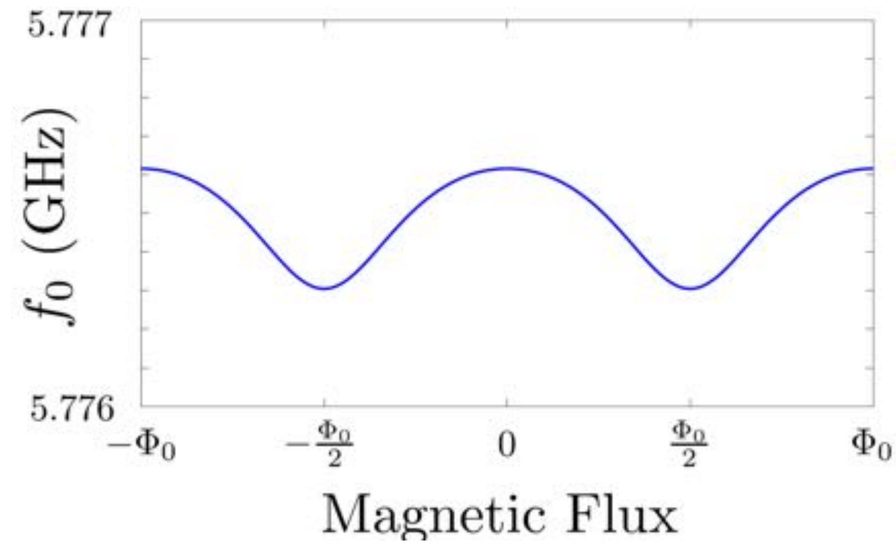
- Naturally multiplexed (~ 1000/line)
- Many GHz HEMT amplifier bandwidth
- Little to none degradation of overall system sensitivity (from μMux)



J.A. Mates et al., *APL* **111**, 062601 (2017)

Principle of operation

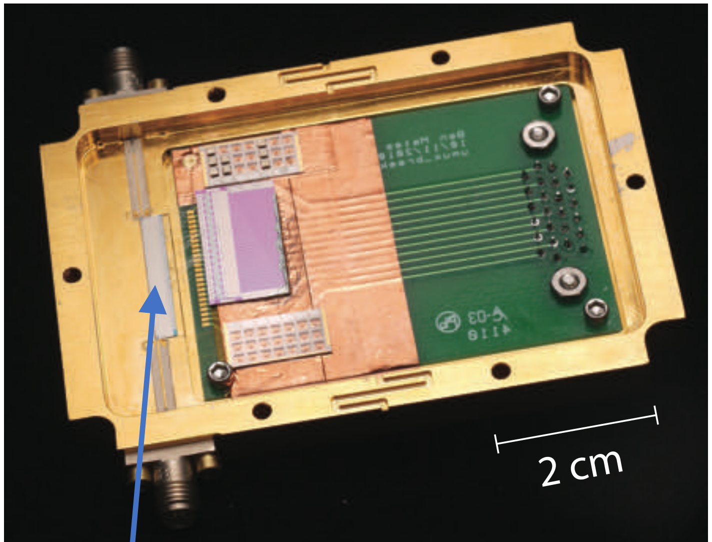




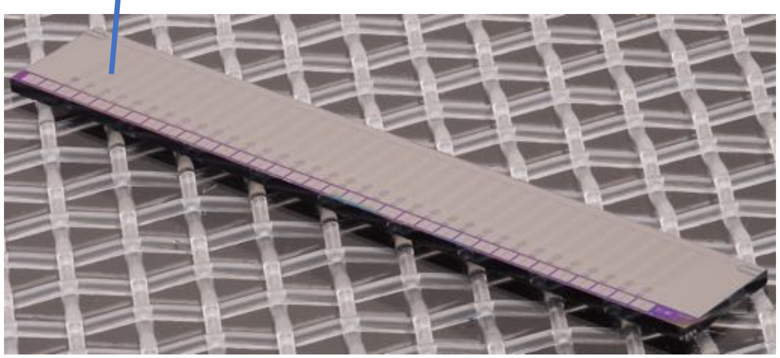
J.A.B. Mates, PhD thesis, 2011

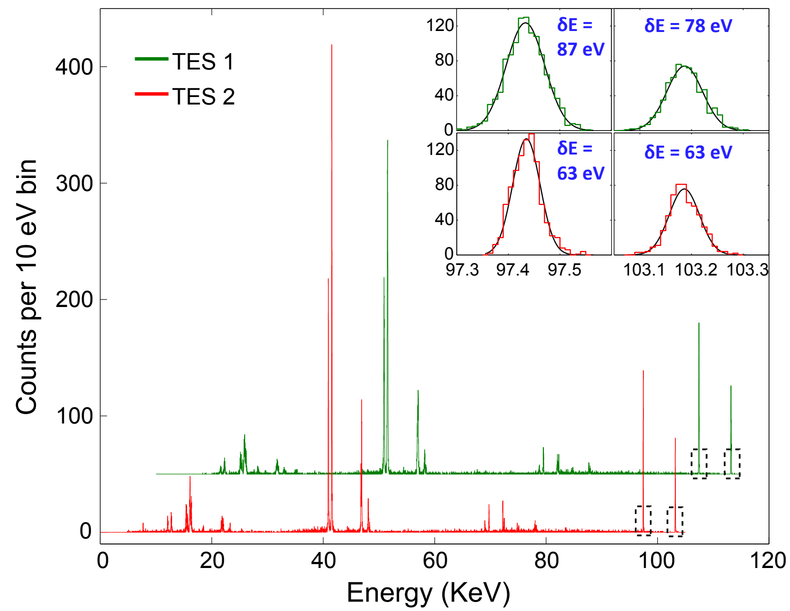
- Changes in TES current induce changes in flux through RF SQUID → changes in SQUID inductance → changes in microwave resonance frequency → changes in microwave transmission S_{21}
- Effectively, TES signal is amplified through ultra-low noise RF SQUID
- Single microwave feedline can read ~ thousand pixels.

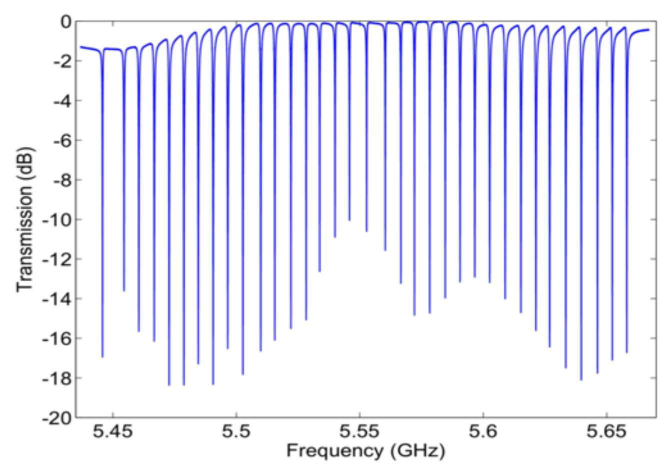
Early µMux readout demonstration for gamma-ray TESs at NIST (2013)



O. Noroozian et al., *APL* **103**, 202602 (2013)







Demonstration of microwave SQUID mux with increased channel count for gamma-ray and x-ray calorimetry (NIST)

APPLIED PHYSICS LETTERS **111**, 062601 (2017)

Simultaneous readout of 128 X-ray and gamma-ray transition-edge microcalorimeters using microwave SQUID multiplexing

J. A. B. Mates,[1,a)] D. T. Becker,[1] D. A. Bennett,[2] B. J. Dober,[2] J. D. Gard,[1]

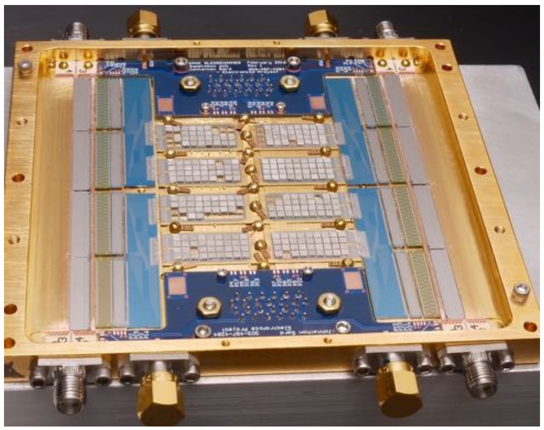
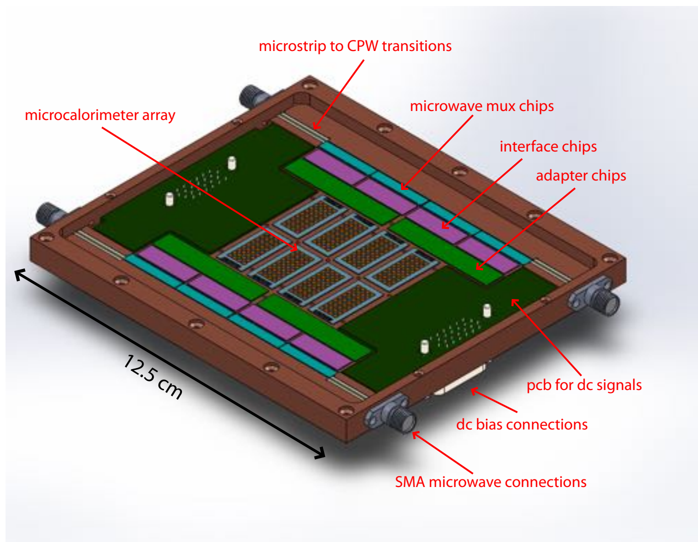


FIG. 2. Photograph of the sample box containing the 8 TES microcalorimeter detector chips (center), 8 microwave multiplexer chips (outer vertical columns) and chips for detector bias, Nyquist filtering, and signal routing.



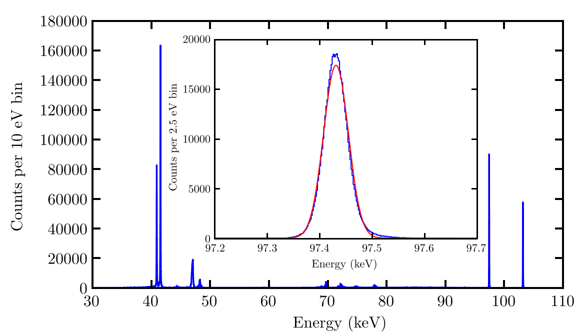
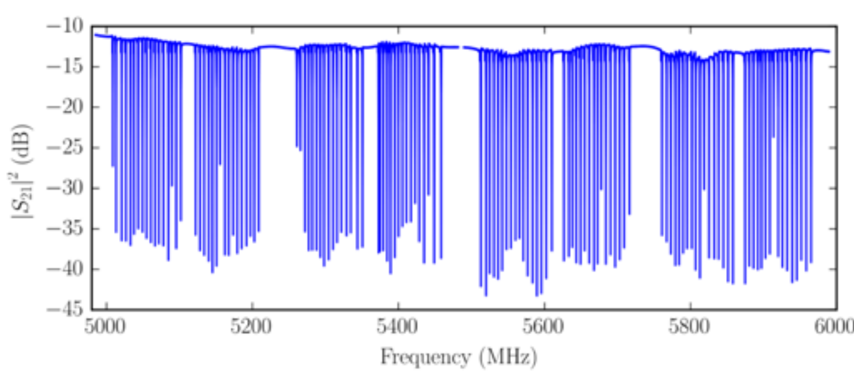
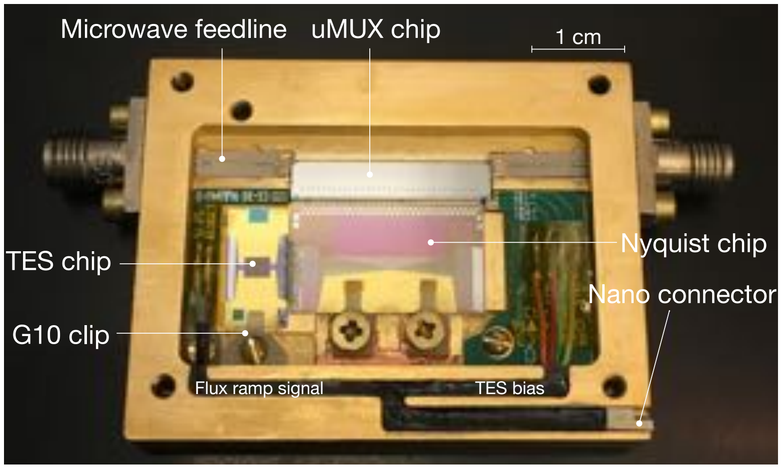
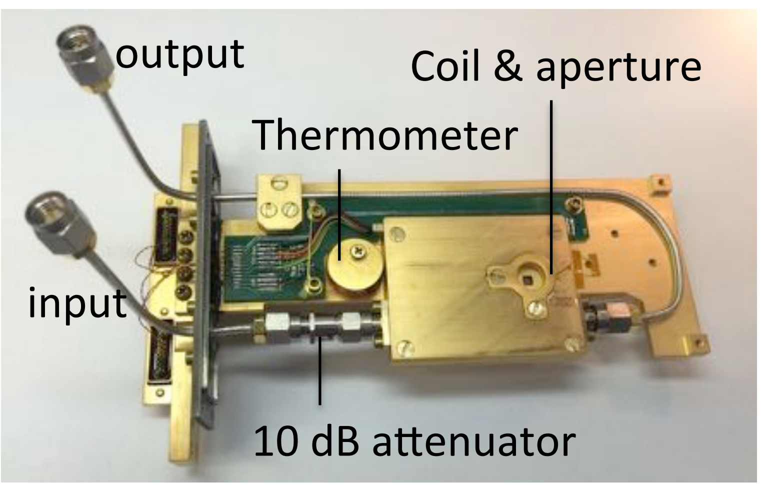


FIG. 5. The combined spectrum from 89 TESs measured simultaneously using microwave SQUID multiplexed readout. The source of the x-rays and gamma-rays was a gadolinium-153 calibration source. The inset shows a zoomed region around the 97 keV gamma-ray peak (blue) with a Gaussian fit FWHM resolution of 55 eV (red).



Demonstration of µMux for X-ray calorimetry on NASA's Lynx telescope (GSFC and NIST)

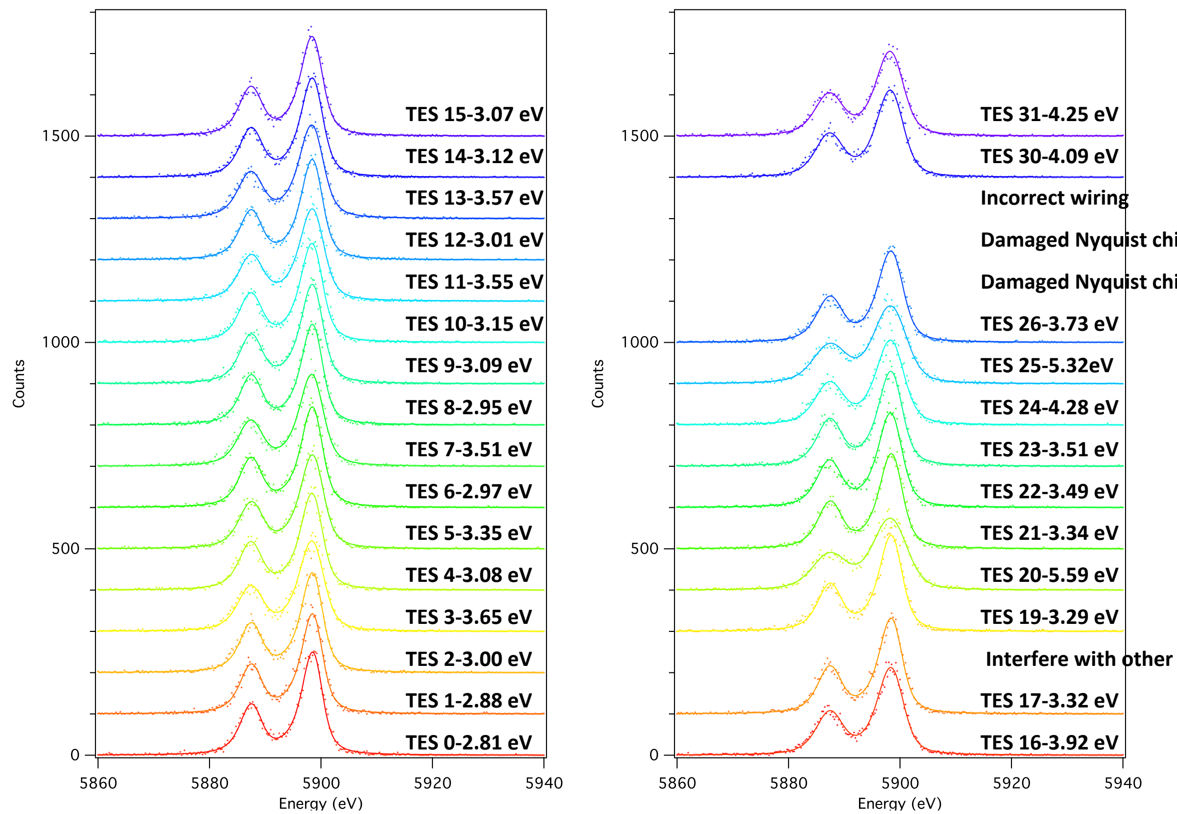




Wonsik Yoon, et al., JLTP, 2018

Successful readout of ~ 30 x-ray TES pixels and 30 spectra for the MnKa line

MnKα X-ray spectrum, R/Rn ~ 20 %



- <ΔE> = 3.53 eV FWHM @ 5.9 keV including all measured pixels

The End

Thank you!

- Quick announcement:

Looking to fill one or two postdoc positions at NASA GSFC to work with us on single-photon MKIDs, EXCLAIM (Microspec/MKID-based balloon mission, and paramps)

If interested please contact:
Omid Noroozian (omid.noroozian@nasa.gov)

Eric Switzer (eric.r.switzer@nasa.gov)

Backup

Flux-ramp modulation/demodulation

- Linearizes output in absence of feedback
- Here, flux ramp signal at 40 KHz applies $\sim 3\Phi_0$ every 25 µs
- Flux ramp much faster than input signal → phase shift ϕ ~ constant during ramp and proportional to TES current: $$\phi = \frac{2\pi M}{\Phi_0} I_{\mathrm{TES}}$$
- For demodulation:

$$\phi = \arctan\left(\frac{\sum V_Q \sin\omega_m t}{\sum V_Q \cos\omega_m t}\right)$$