Far-IR Kinetic Inductance Detectors

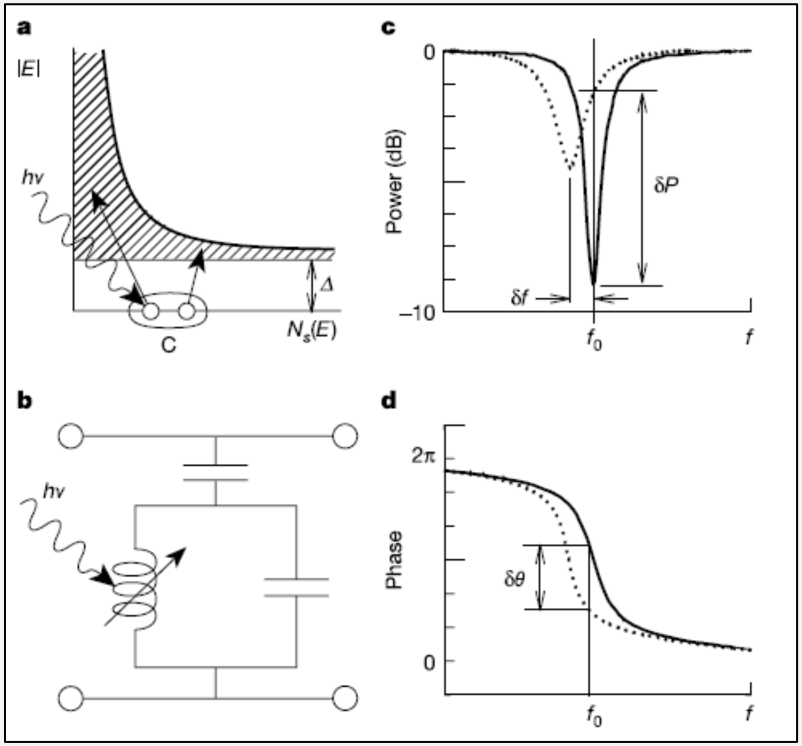
SOFIA Instrument Roadmap Workshop II

Steve Hailey-Dunsheath, Caltech

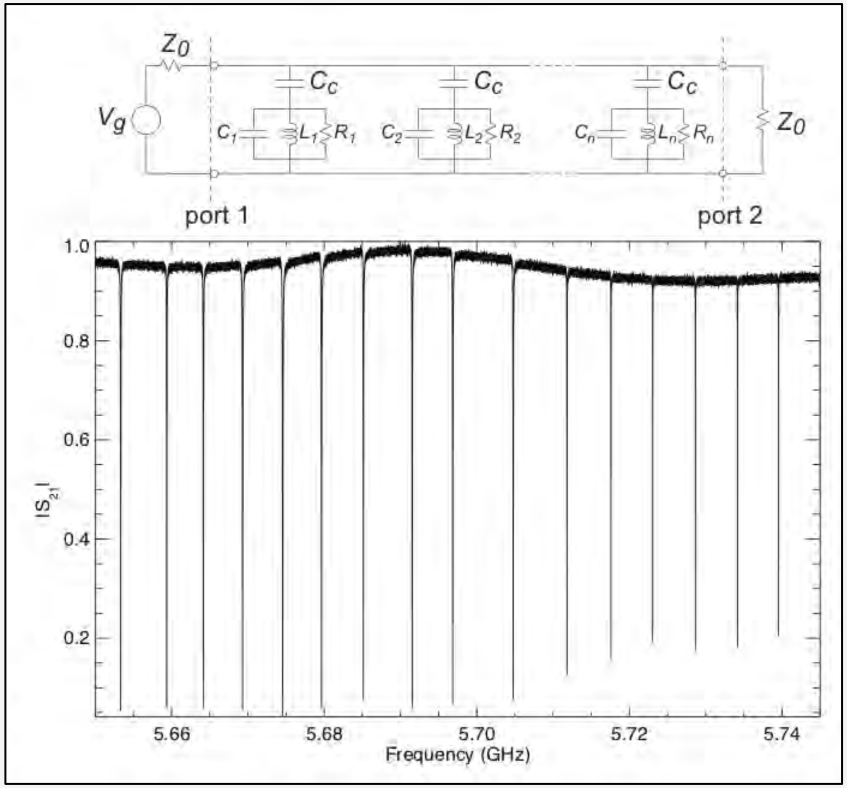
July 27, 2020

Introduction to KIDs

- At T = 0 the surface impedance of a superconductor is $Z_s = j\omega L_s$
- Kinetic Inductance is associated with inertia of Cooper Pairs
- Photons with E > 2Δ (ν > 100 GHz for Al) break Cooper Pairs --> **$\delta Z_s = R_s + j\omega\delta L_s$**
- Natural frequency domain multiplexing
- Readout frequencies vary from RF to microwave (e.g., 0.2 – 10 GHz)

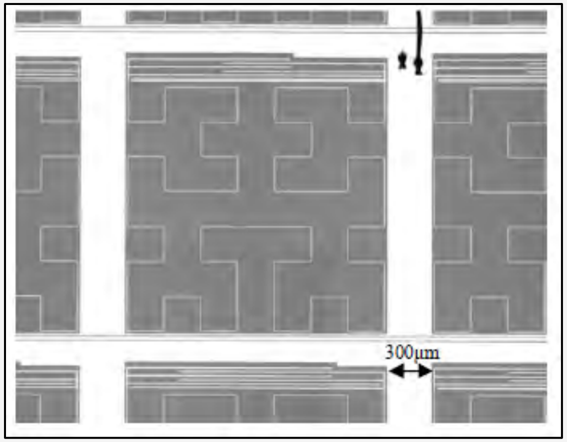


Day+03

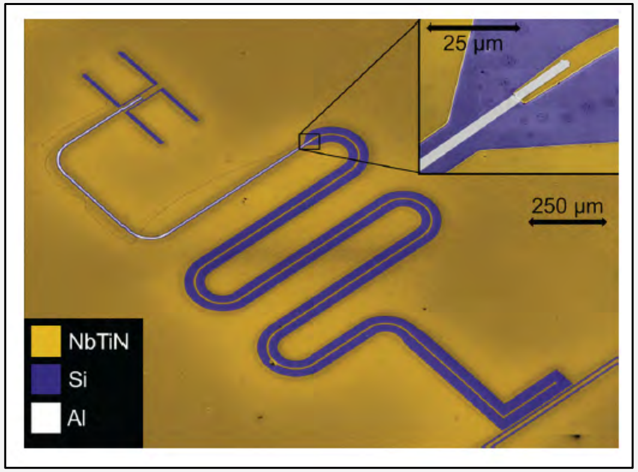


Credit: J. Zmuidzinas

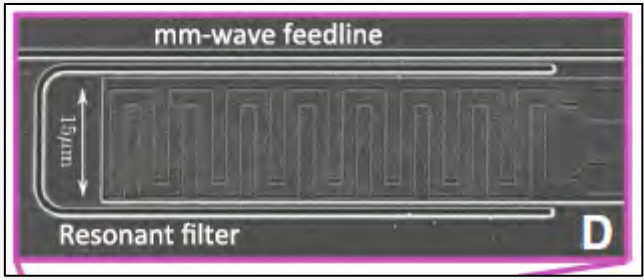
Ground-Based Implementation in Sub/mm



NIKA pixel; Goupy+16



Janssen+13



Wheeler+18

NIKA2 on IRAM 30m:

- Lumped element Al
- f_{reso} ~ 1 GHz
- subarrays with ~1,000 pixels at 150 GHz, 260 GHz
- 2,900 total detectors

CSO demonstrators:

- **MUSIC:** 2,300 pixels 0.87mm – 1.98mm
- **MAKO:** 432 pixels at 350 μm

SRON/Delft demonstrator:

- Antenna-coupled quarter-wave cpw resonator, Al/NbTiN hybrid
- f_{reso} ~ 5 GHz
- Demonstrated on Apex at 350 GHz, 850 GHz
- SPACEKIDs demo 961 detector array
- NEP = 3×10^{-19} W/Hz$^{0.5}$

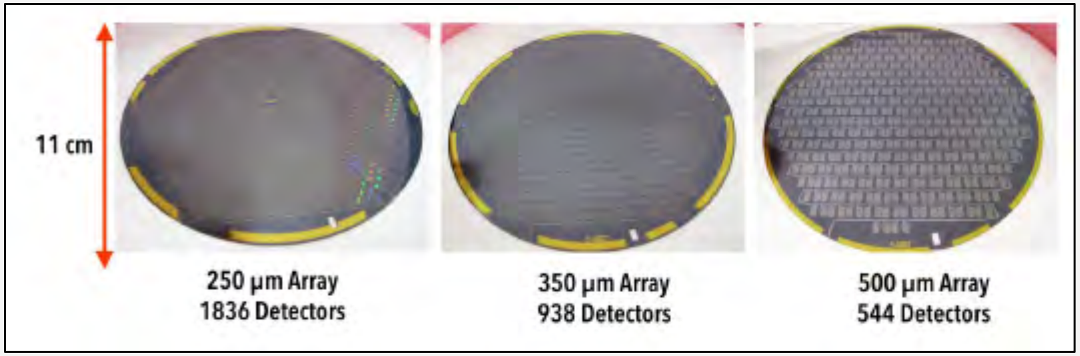
SuperSpec:

- Antenna-coupled lumped element TiN
- f_{reso} ~ 300 MHz
- On-chip spectrometer at 250 GHz, R = 300
- 100 – 300 detectors / chip
- NEP = 6×10^{-19} W/Hz$^{0.5}$

Balloon Payloads

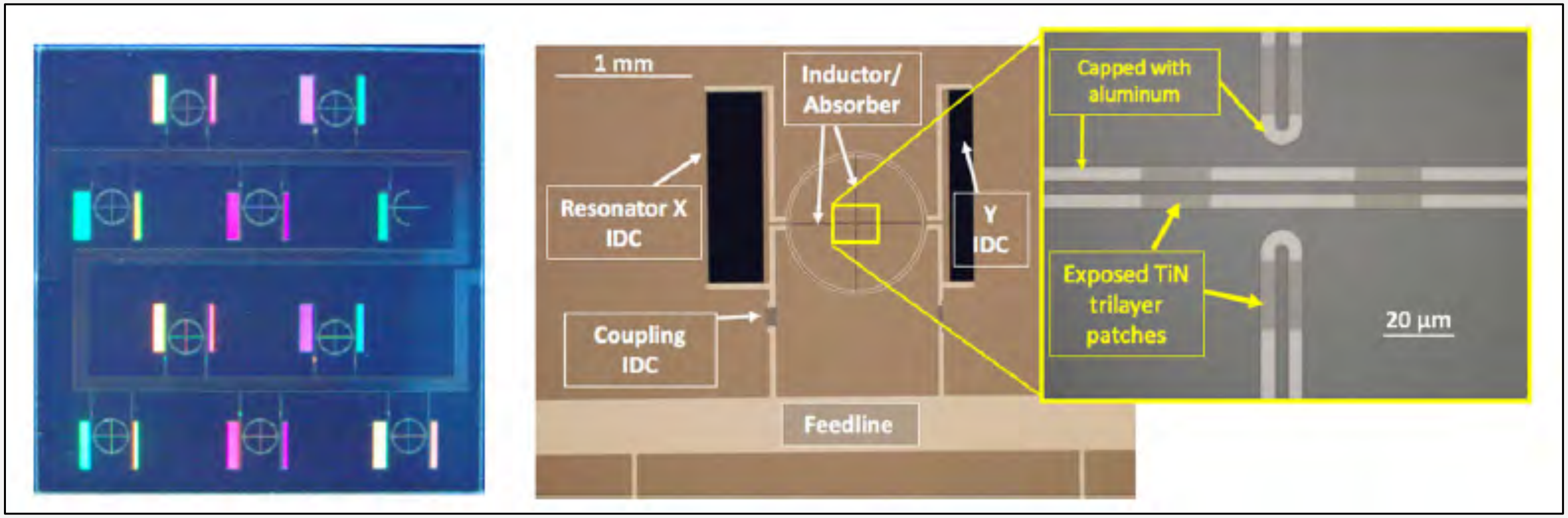
Project	wave [μm]	mode	N_{det}	flight
OLIMPO	650, 850, 1200, 2000	broadband / FTS	120	2018
BLAST-TNG	250, 350, 500	broadband polarimetry	3,318	2020
EXCLAIM	555 - 714	R = 512 on-chip spectrometer	2,130	~2021
TIM	**240 - 420**	**R = 250 grating spectrometer**	**7,136**	**~2023**

BLAST-TNG Arrays



Lourie+18

BLAST-TNG / TolTEC Pixel



TolTEC pixel; Austermann+18

TIM Collaboration

University of Illinois J. Vieira (PI), J. Filippini, F. Fu, **R. Nie**

Caltech/JPL M. Bradford, B. Bumble, S. Hailey-Dunsheath, **R. Janssen**, H. LeDuc, **L. Liu**, J. Redford

Arizona State University C. Groppi, J. Hoh, H. Mani, J. Matthewson, A. Sinclair, M. Underhill

University of Arizona D. Marrone, R. Keenan, I. Trumper

University of Pennsylvania J. Aguirre, A. Corso, J. Bracks

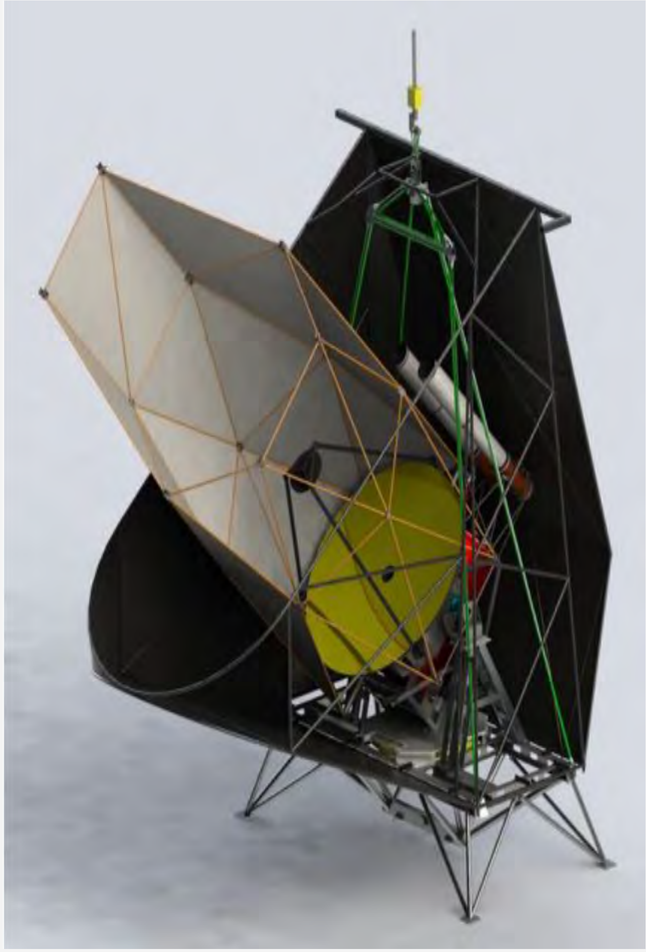
University of Chicago / Argonne P. Barry

Other Collaborators M. Bethermin, T. Chang, M. Devlin, O. Doré, G. Holder, K. Keating, E. Kovetz, G. Lagache, P. Mauskopf, D. Narayanan, G. Popping, E. Shirokoff, R. Somerville, B. Uzgil, J. Zmuidzinas

TIM (Terahertz Intensity Mapper*)

*Formerly STARFIRE

- Balloon-borne far-IR spectrometer to study the cosmic star formation history
- Two diffraction grating spectrometer modules to cover 240 – 420 μm spectral band at R = 250
- Use intensity mapping and individual galaxy observations to observe a large cosmic volume in 0.5 < z < 1.5
- Detect [CII] 158 μm power spectrum, and [CII] x [NII] 122 μm cross-power spectrum
- Duplicate BLAST-TNG gondola, cryostat, readout electronics, and pointing system
- 2.0 meter primary mirror

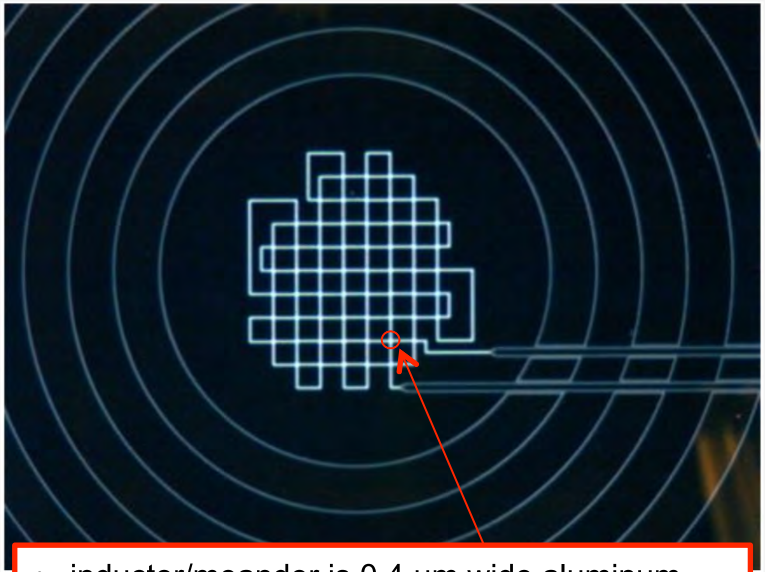


Vieira+19

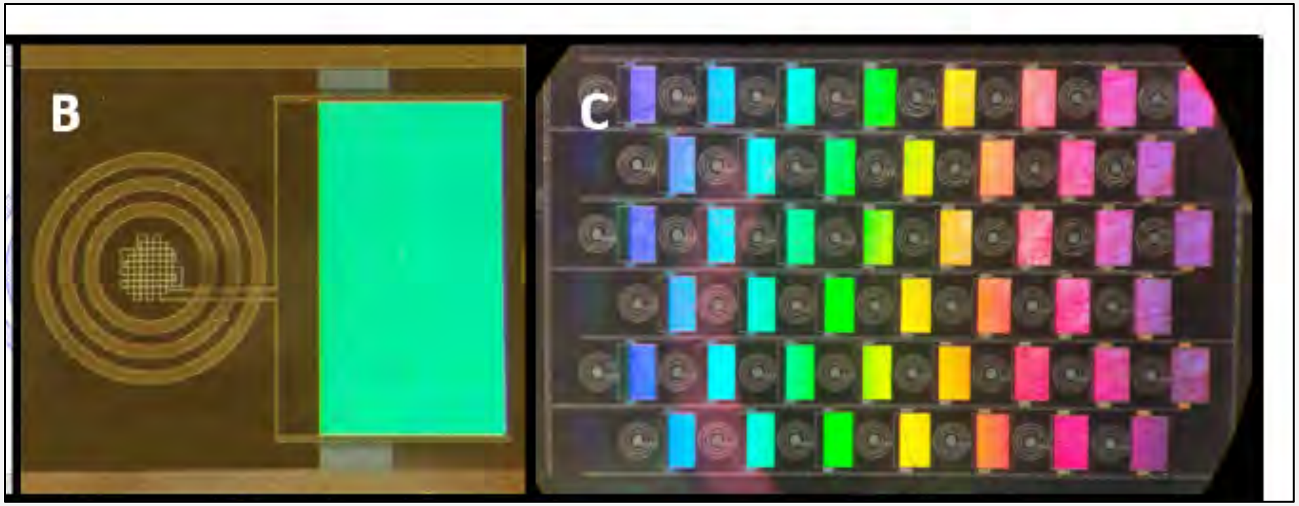
Detector Approach

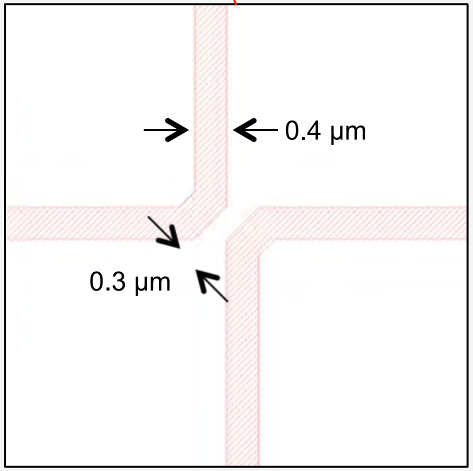
Detector Design Parameters

- **Approach**: Lumped-element aluminum KIDs
- **Number of pixels**: x2 arrays of 3,000 – 4,000 detectors each
- **Optical coupling**: circular waveguide; backside etching to provide backshort optimized for 240 – 420 μm
- **Feedhorns**: Direct-drilled, multi-flare angle horns
- **Pixel pitch**: 2.3mm, hex-pack
- **Lithography**: single layer 20 – 40 nm Al film
- **KID Resonant frequencies**: 0.5 – 1.0 GHz (possible extension to 2.0 GHz)
- **Target detector NEP**: 4 x 10^{-18} W/Hz$^{0.5}$ (goal), 1 x 10^{-17} W/Hz$^{0.5}$ (requirement)



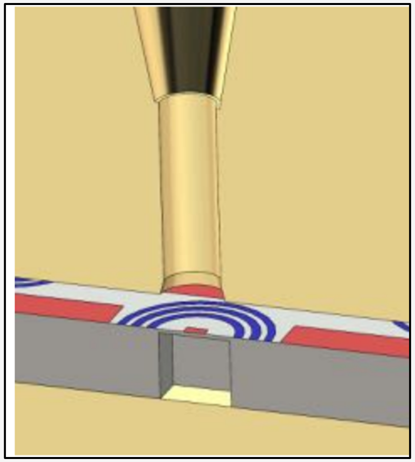
- inductor/meander is 0.4 μm wide aluminum
- 0.3 μm gap at each intersection provides a capacitive short

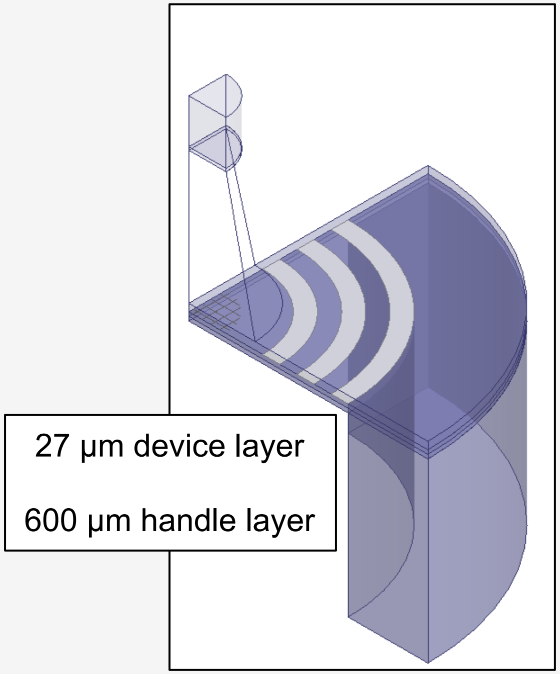


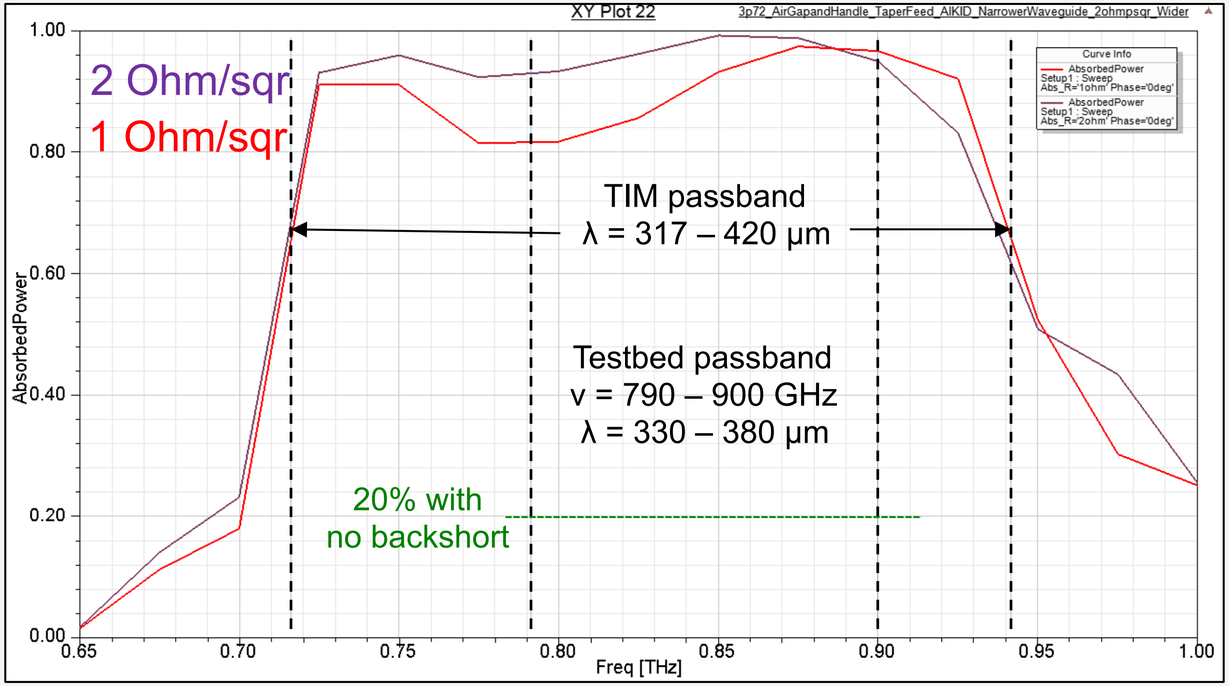


Optical Coupling

- Absorber couples to circular waveguide / direct-drilled horn
- 3 concentric annular rings on the wafer surface help eliminate conversion into substrate modes
- Backshort formed by backside etching in SOI wafer, 27 µm from absorber, then depositing low Tc aluminum (cosmic ray mitigation)
- Simulate band-averaged 95% coupling with 2 Ω/□ surface impedance, 20% with no backshort (**measure 17%**)



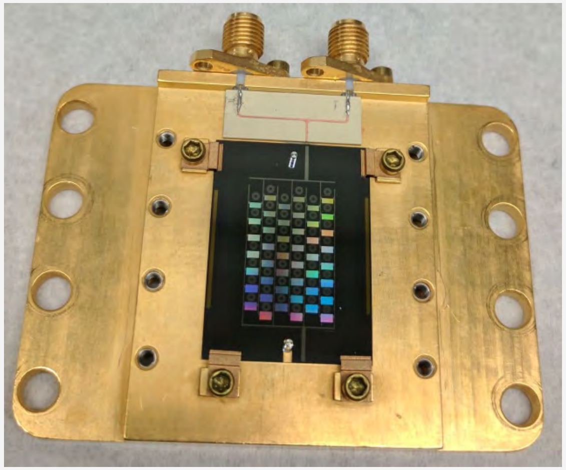


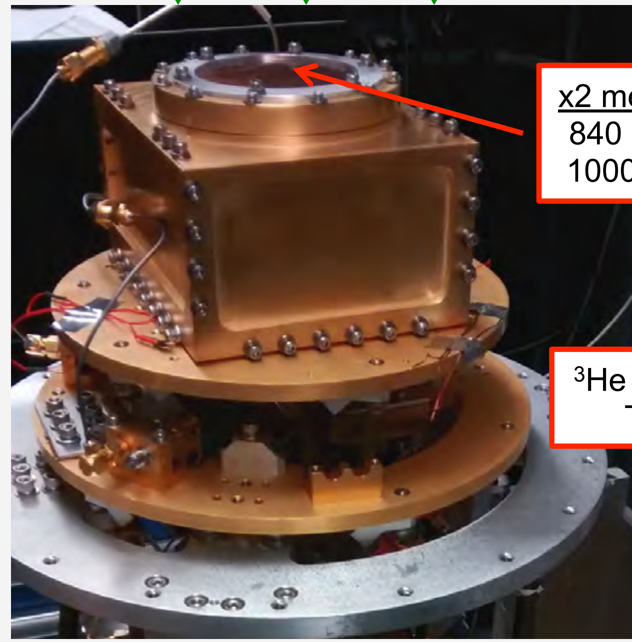


HFSS simulations from T. Reck (JPL)

Detector Package / Testbed

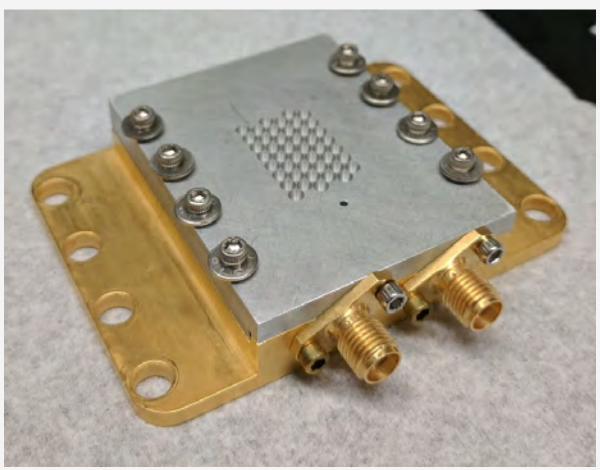
cryogenic blackbody

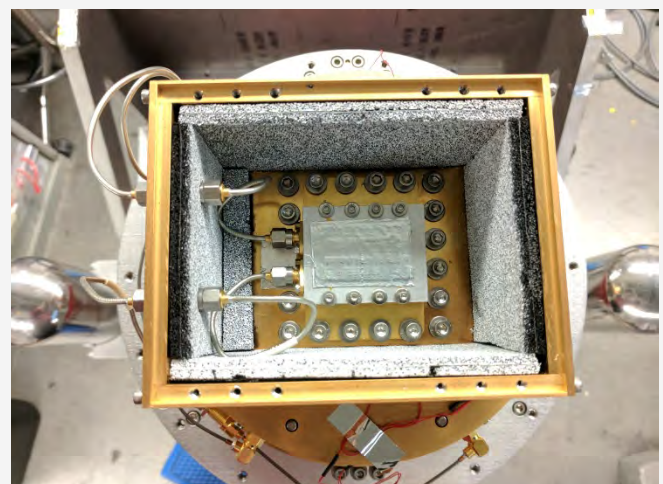




x2 metal-mesh filters
840 GHz bandpass
1000 GHz low-pass

^{3}He sorption fridge
T > 210 mK

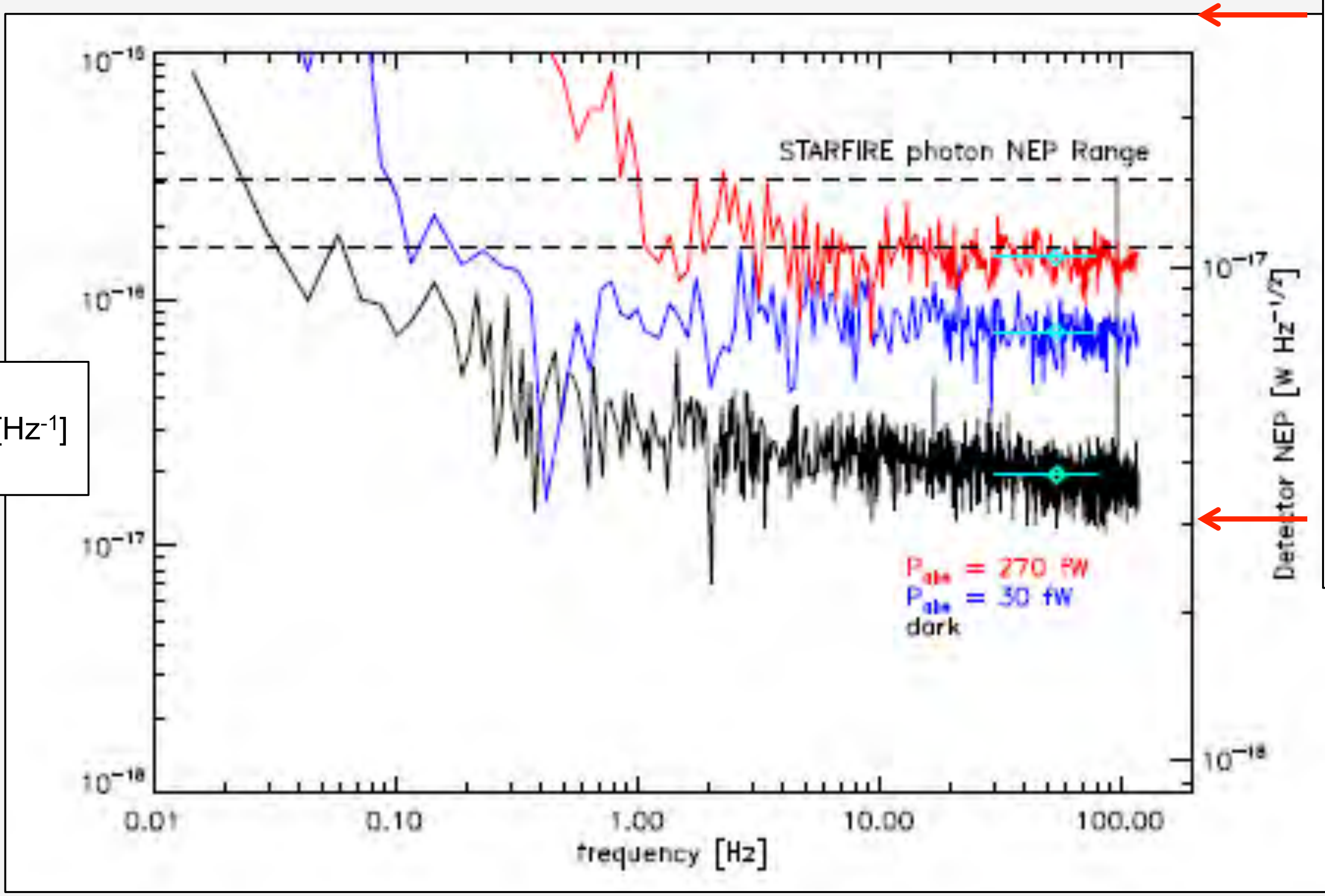




Optical Testing: Photon Noise

SOFIA
Background-limited NEP
λ = 100 μm, R = 10^3
NEP ~ 3 x 10^{-17} W/$Hz^{0.5}$

S_{xx} [Hz^{-1}]



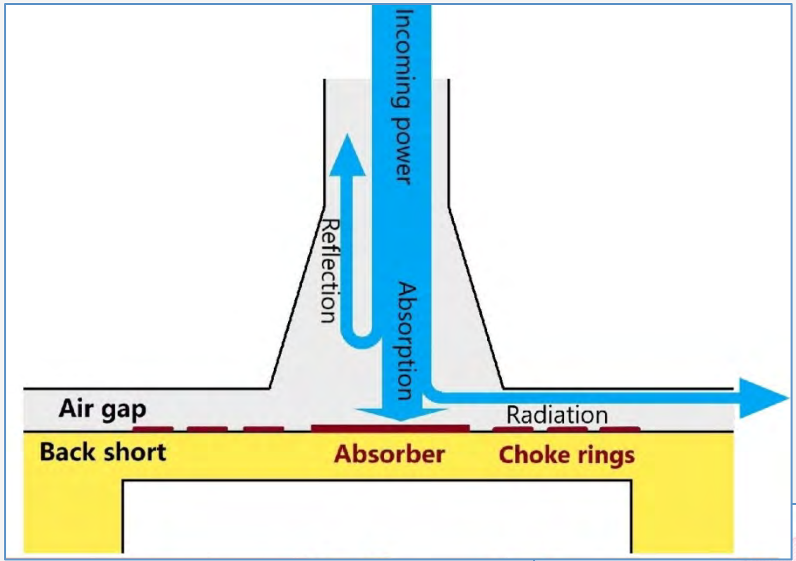
Background-limited NEP
λ = 100 μm, R = 10^5
NEP ~ 3 x 10^{-18} W/$Hz^{0.5}$

Hailey-Dunsheath+18

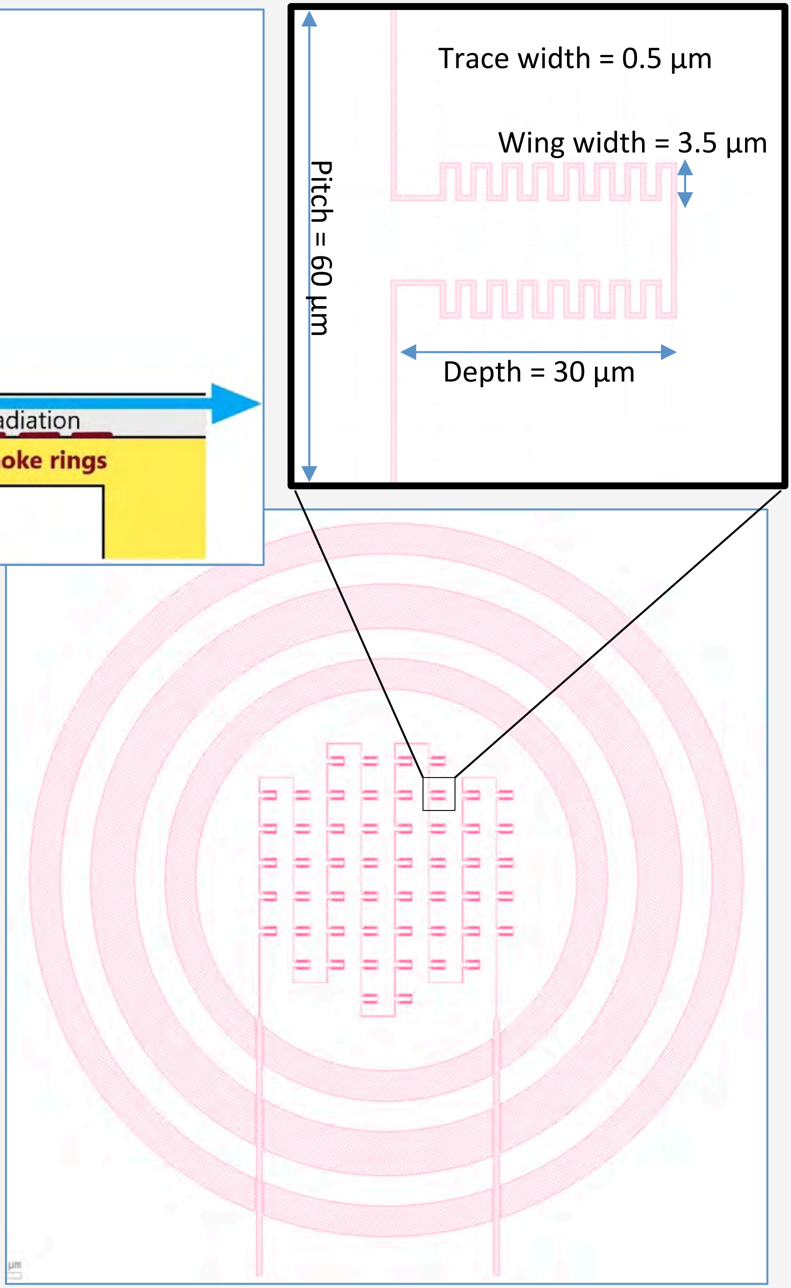
- White noise **NEP = 4 x 10^{-18} W/root(Hz)**
- Dark noise flat down below 1 Hz
- Close to meeting requirement for SOFIA background-limited operation at R = 10^5

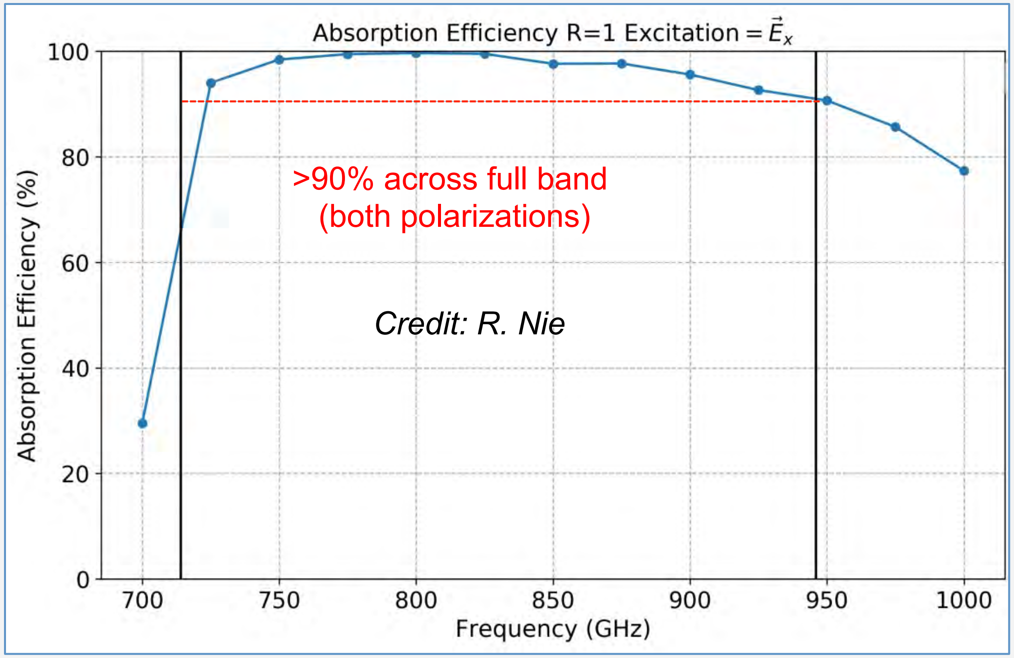
Optimized Absorber Design

- Reoptimize absorber for with 1 Ω/□ surface impedance
- Increase feature width from 0.3 µm to 0.5 µm
- ~95% band-averaged absorption
- ~0.3% band-averaged leakage



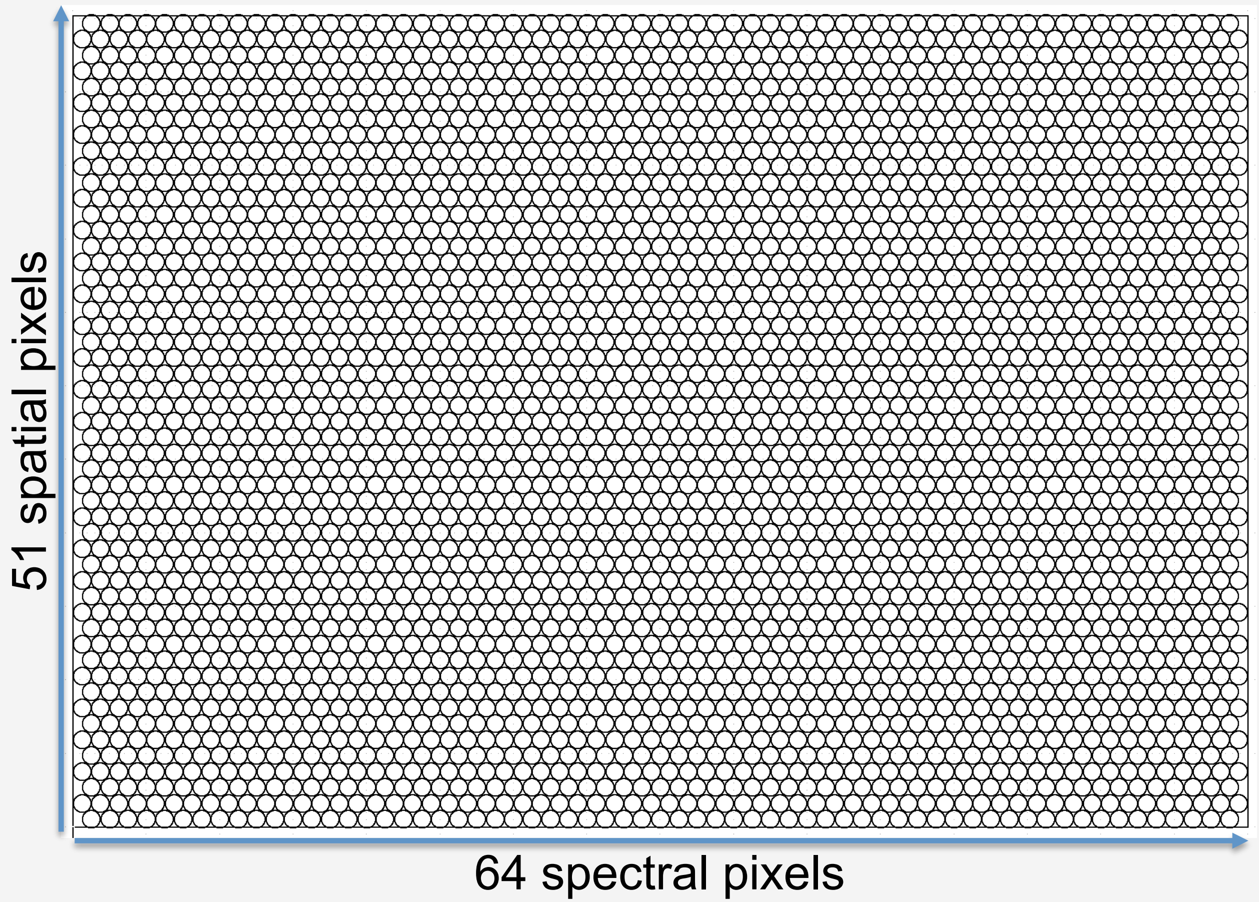
Nie+, submitted



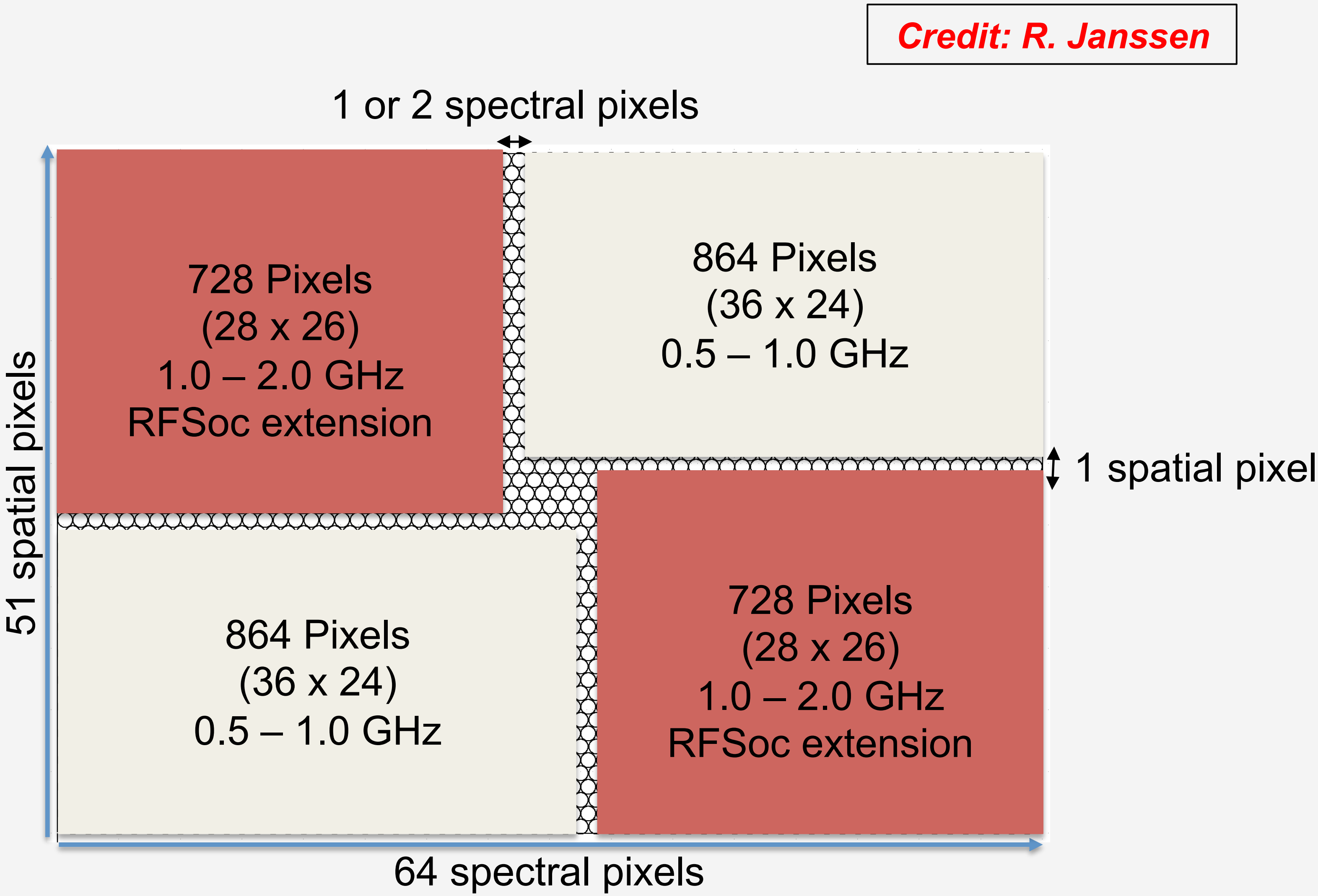


TIM LW Array Layout

Credit: R. Janssen

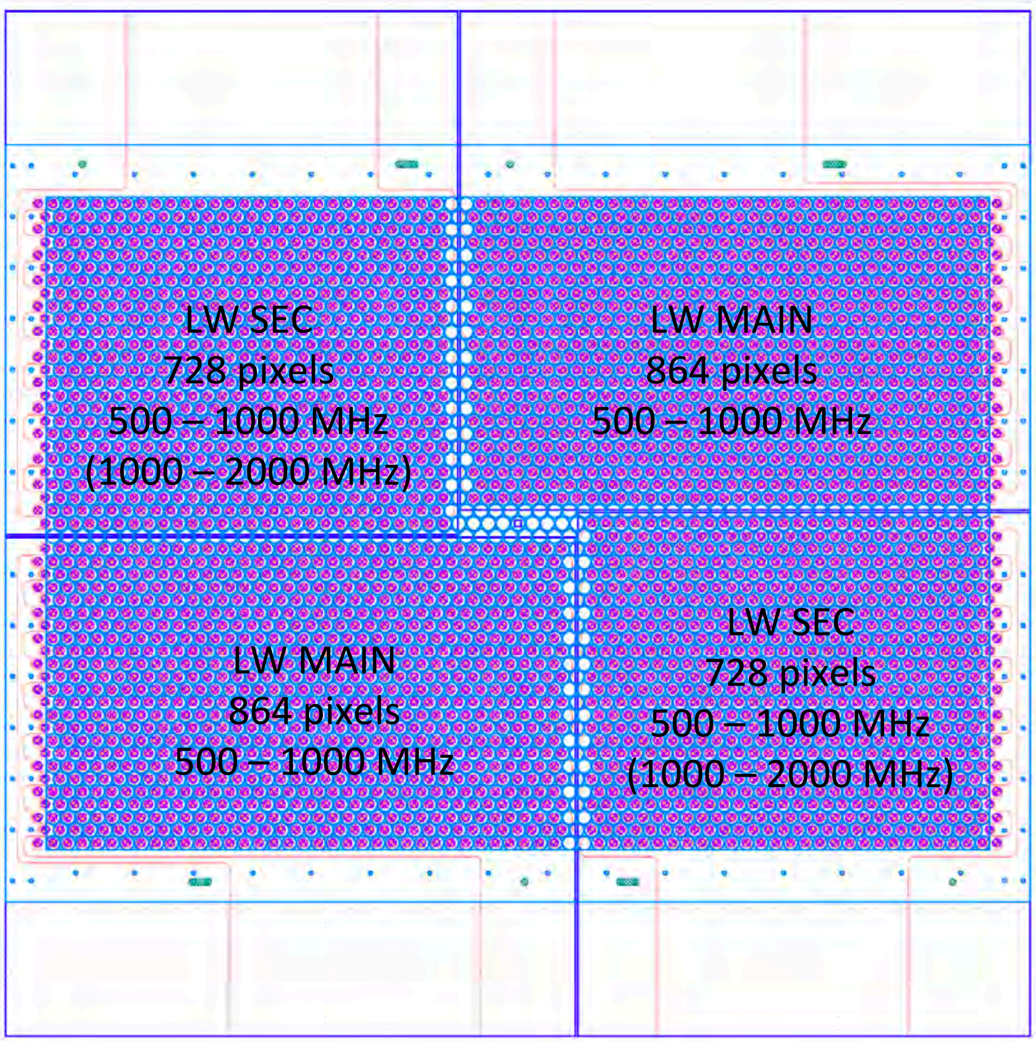


TIM LW Array Layout



Long Wavelength Module

Array	Pitch (um) [Spectral x Spatial]	# Spectral Pixels (X)	# Spatial Pixels (Y)	Readout Frequency (MHz)
LW main*	2300 x 1992	36	24	550 – 950 [10 MHz gap @ 750 MHz]
LW secondary*	2300 x 1992	28	26	1050 – 1950 [20 MHz gap @ 1500 MHz]



RFSoC has 4 separate channels

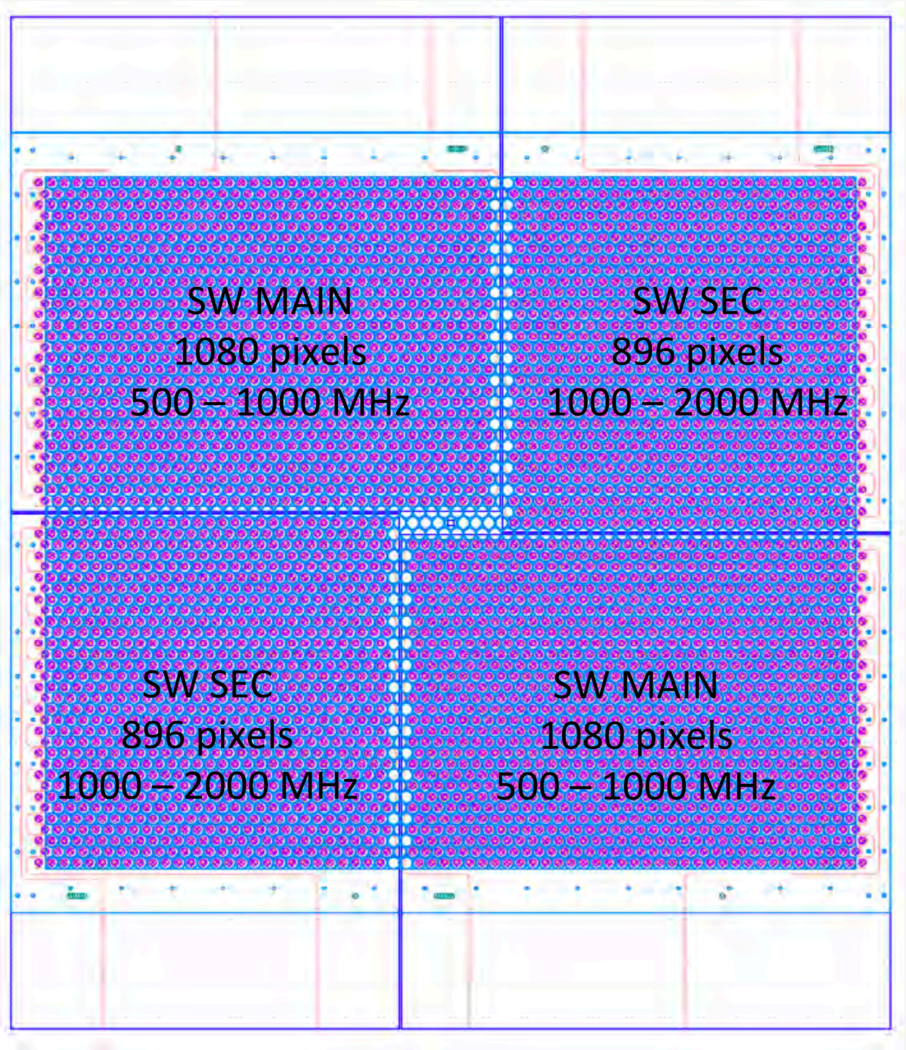
Current firmware allows 1000 pixels per channel in a 500 MHz band, so baseline is one RFSoC per module

Extension of RFSoC to more channels and 2 GHz bandwidth would allow daisy chaining one Main and one Secondary array

Credit: R. Janssen

Short Wavelength Module

Array	Pitch (um) [Spectral x Spatial]	# Spectral Pixels (X)	# Spatial Pixels (Y)	Readout Frequency (MHz)
SW main*	2300 x 1992	36	30	550 – 950 [10 MHz gap @ 750 MHz]
SW secondary*	2300 x 1992	28	32	1050 – 1950 [20 MHz gap @ 1500 MHz]



RFSoC has 4 separate channels

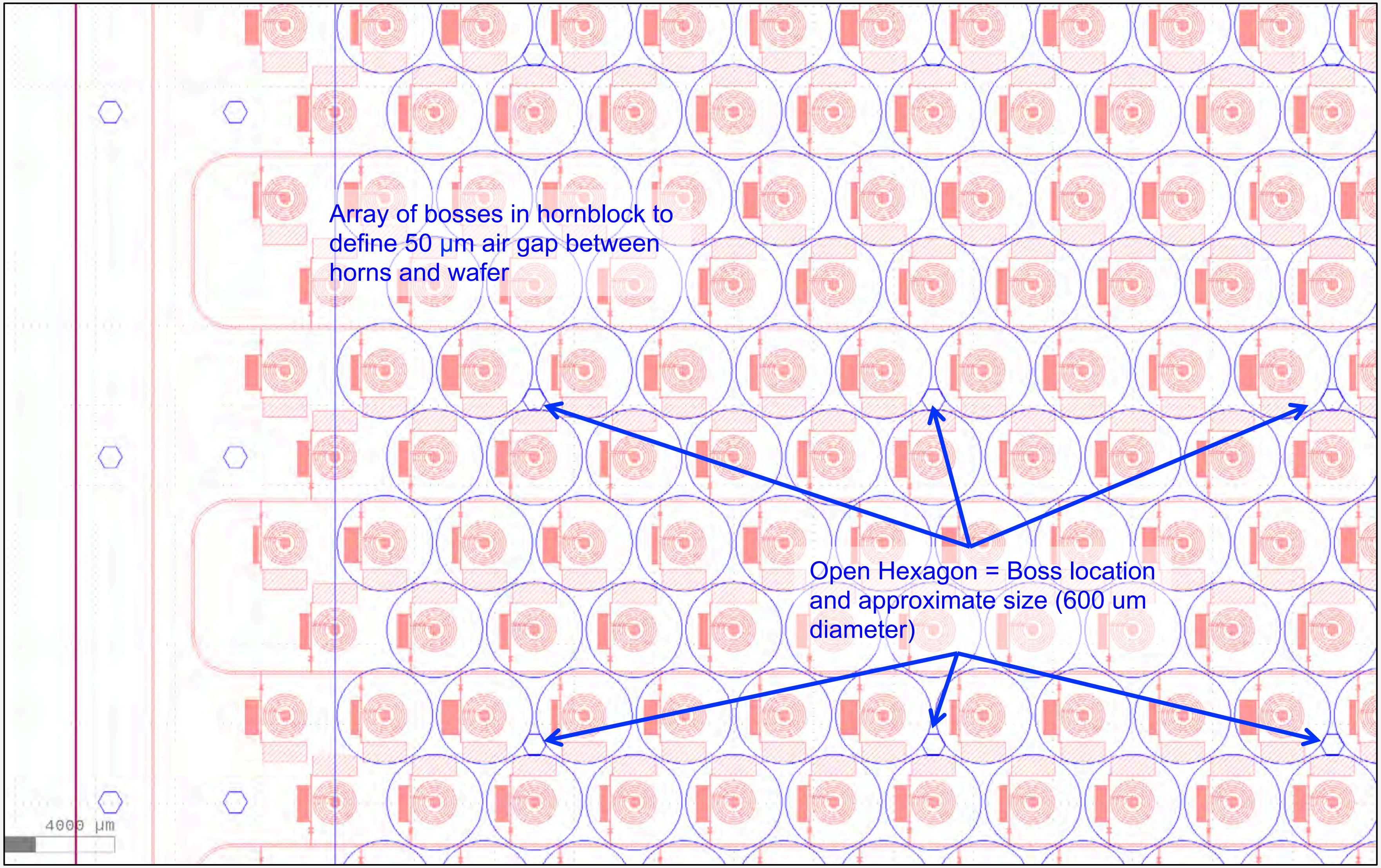
Current firmware allows 1000 pixels per channel in a 500 MHz band, so baseline is one RFSoC per module

Extension of RFSoC to more channels and 2 GHz bandwidth would allow daisy chaining one Main and one Secondary array

Credit: R. Janssen

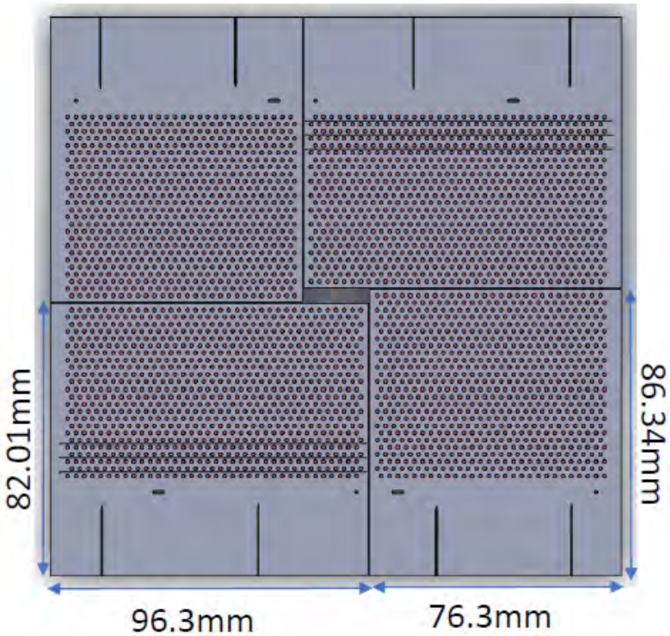
Layout – Boss Placement

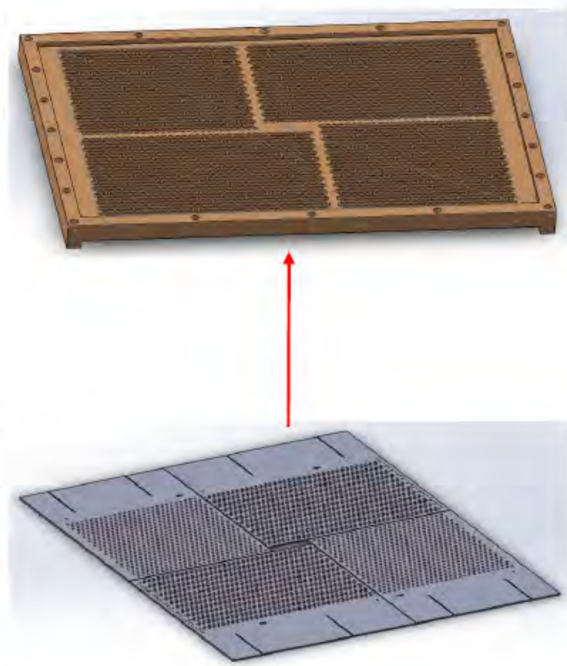
Credit: R. Janssen

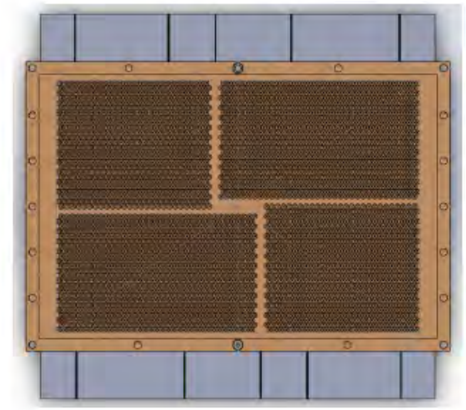


TIM Detector Assembly

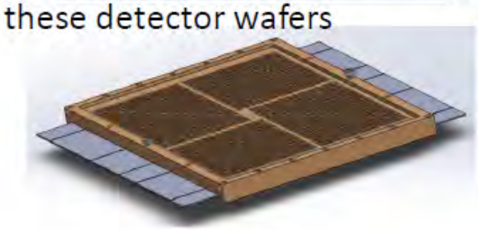
Attach detector wafers



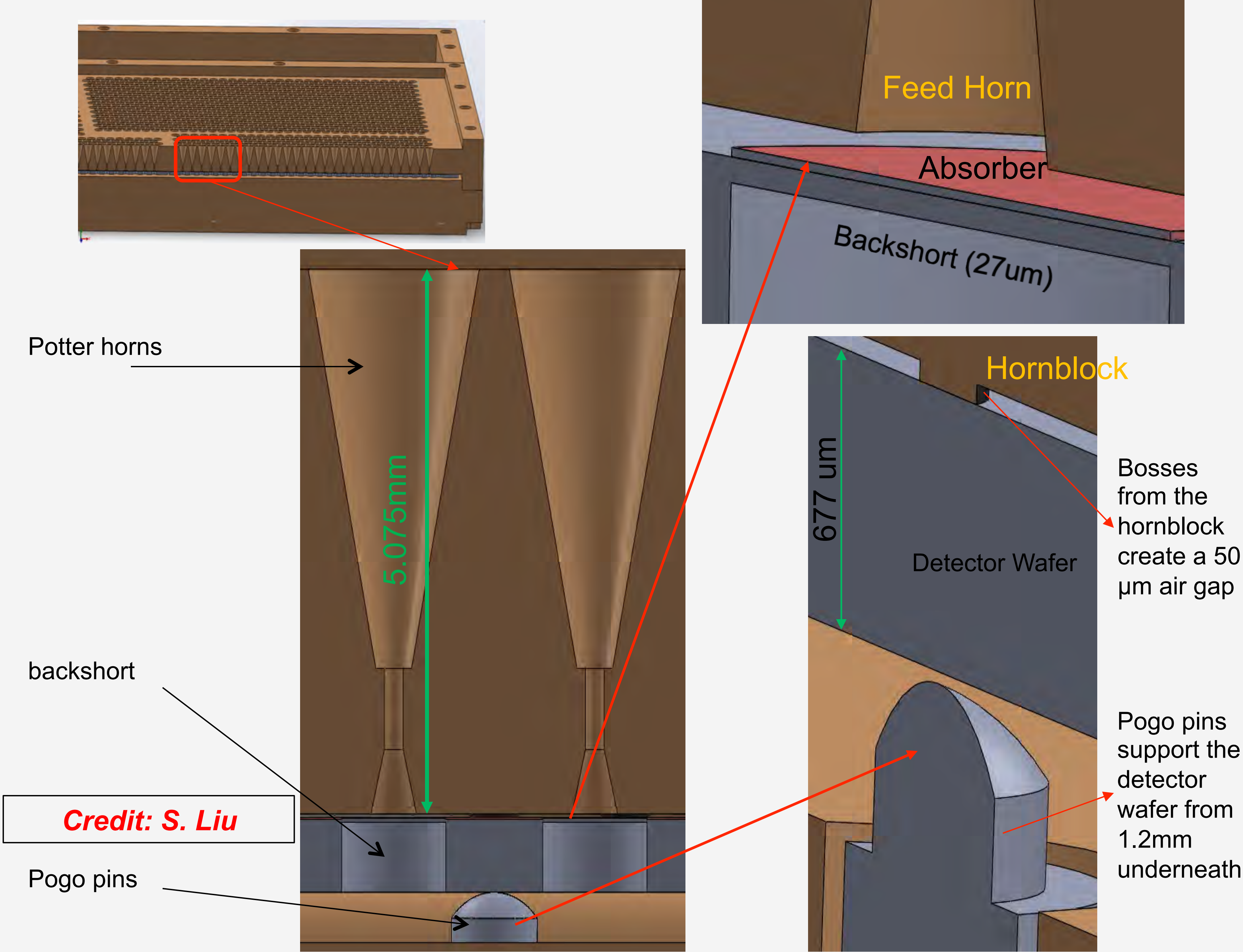




The pin and slot are for positioning these detector wafers



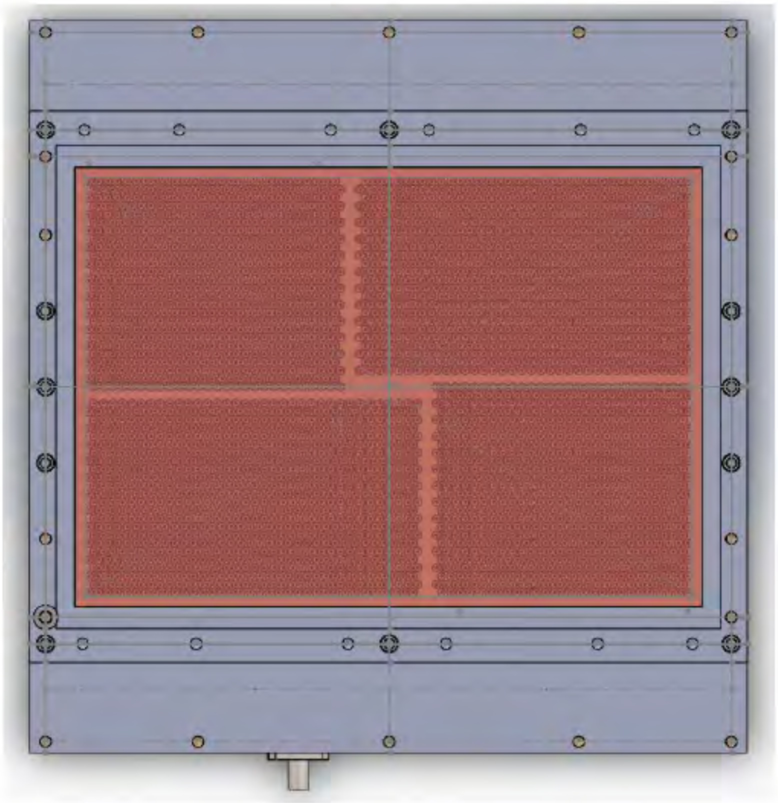
Credit: S. Liu

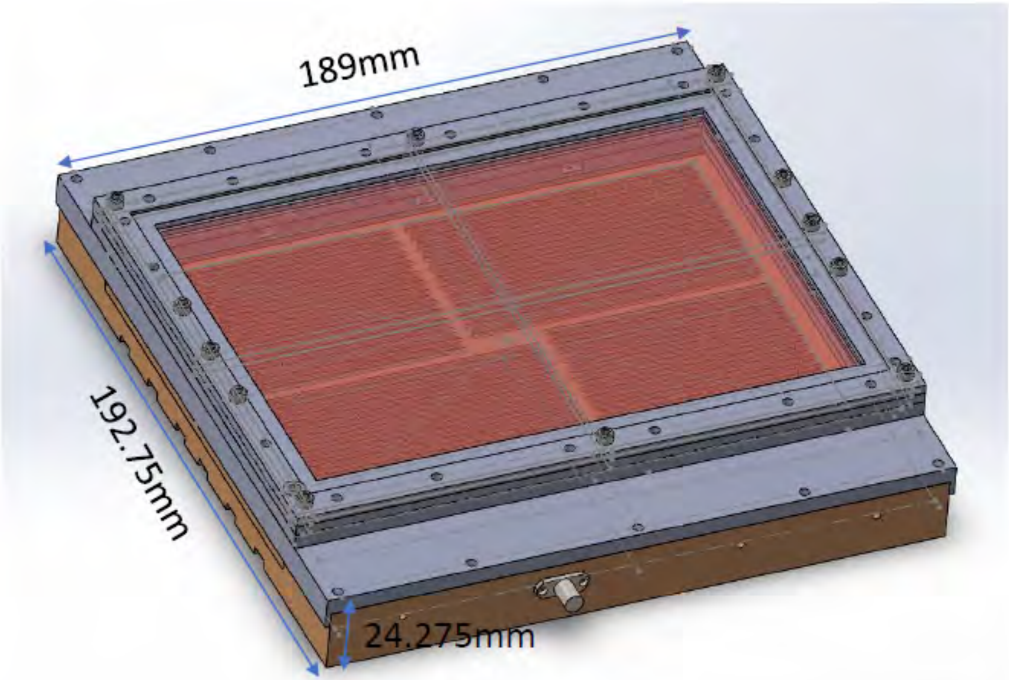


Feed Horn
Absorber
Backshort (27um)
Potter horns
5.075mm
Hornblock
677 um
Detector Wafer
Bosses from the hornblock create a 50 μm air gap
backshort
Credit: S. Liu
Pogo pins support the detector wafer from 1.2mm underneath
Pogo pins

TIM Detector Assembly

Overview





Credit: S. Liu

TIM Readout

Fallback: 4 ROACH2-based readout systems

- BLAST heritage
- 4 CASPER ROACH2
- 4 MUSIC ADC/DAC
- 4x512 MHz bandwidth (0.5 – 1.0 GHz)
- 1024 tones per channel
- 45 W / ROACH2 (45 mW / detector)

Baseline: 2 RFSoC readout system

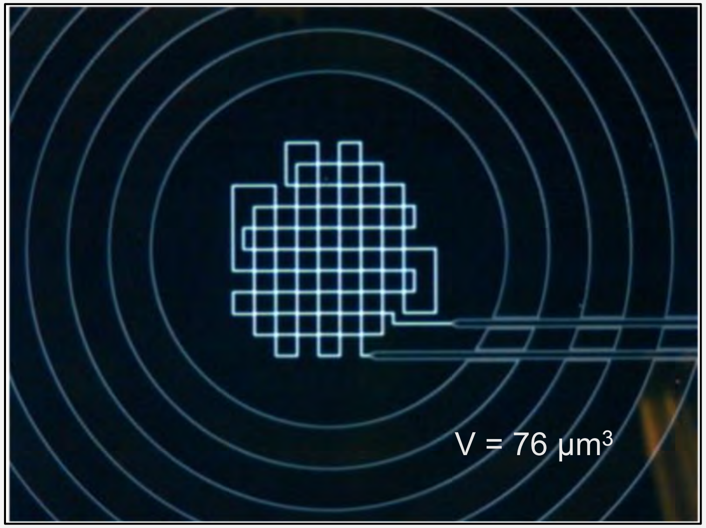
- Xilinx Ultrascale+ FPGA
- 4x 2 GHz bandwidth (0.0 – 2.0 GHz)
- Reduced power consumption
- Use BLAST-TNG firmare

Goal: 1 RFSoC readout system

- Xilinx Ultrascale+ FPGA
- 4x 2 GHz bandwidth (0.0 – 2.0 GHz)

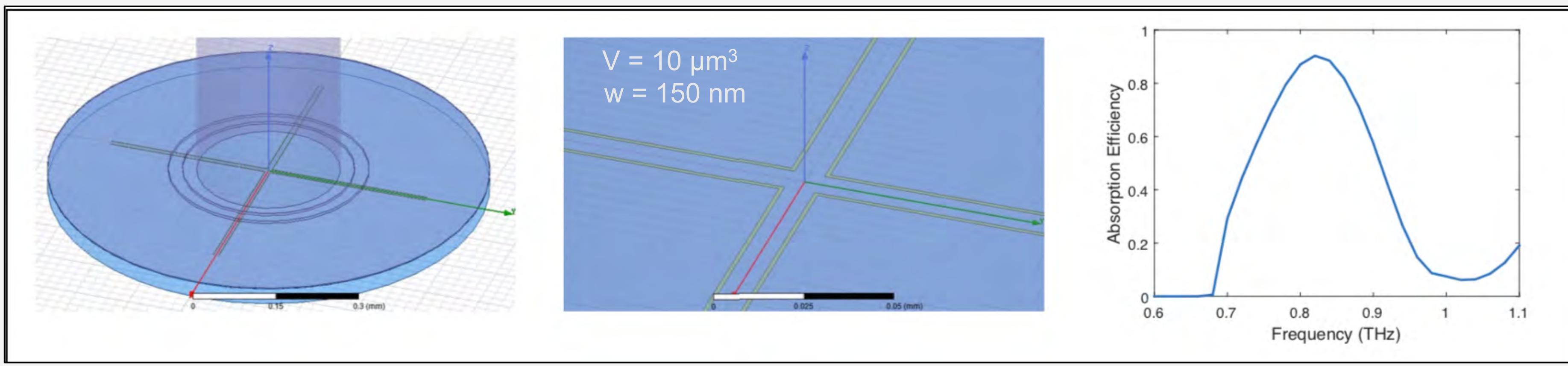
Credit: C. Groppi, A. Sinclair

Reducing the NEP



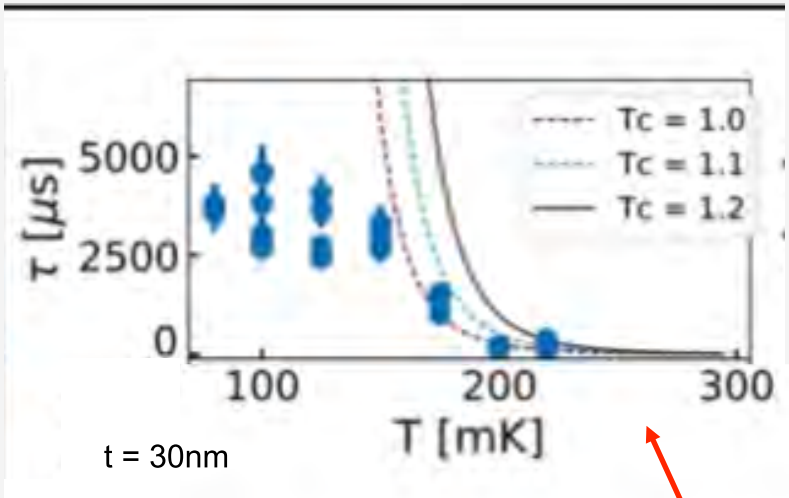
- Move from an impedance-matched sheet across the full waveguide to a line (or cross).
- Reduce volume from 76 µm^3 to <10 µm^3
- Improve quasiparticle lifetimes with better films and lower temperature (τ_{qp} = 30 µs --> 1000 µs)
- τ_{qp} = 1000 µs demonstrated (A. Fyhrie et al. 2020)

$$R_x = \frac{\alpha\gamma S_2(\omega)}{4N_0\Delta_0}\frac{\eta_0\tau_{qp}}{\Delta_0 V_L},$$

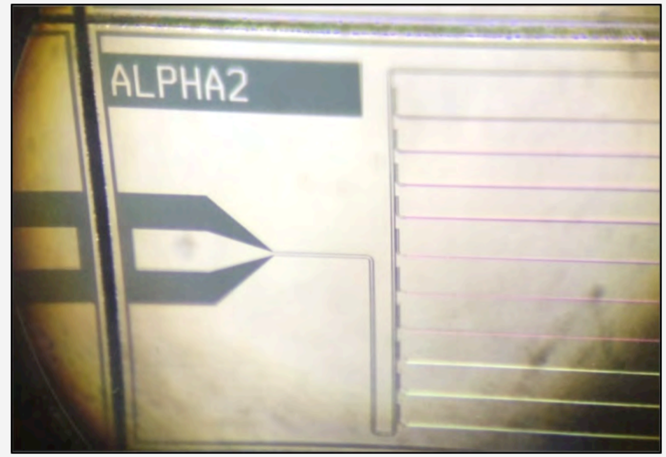


Credit: P. Day

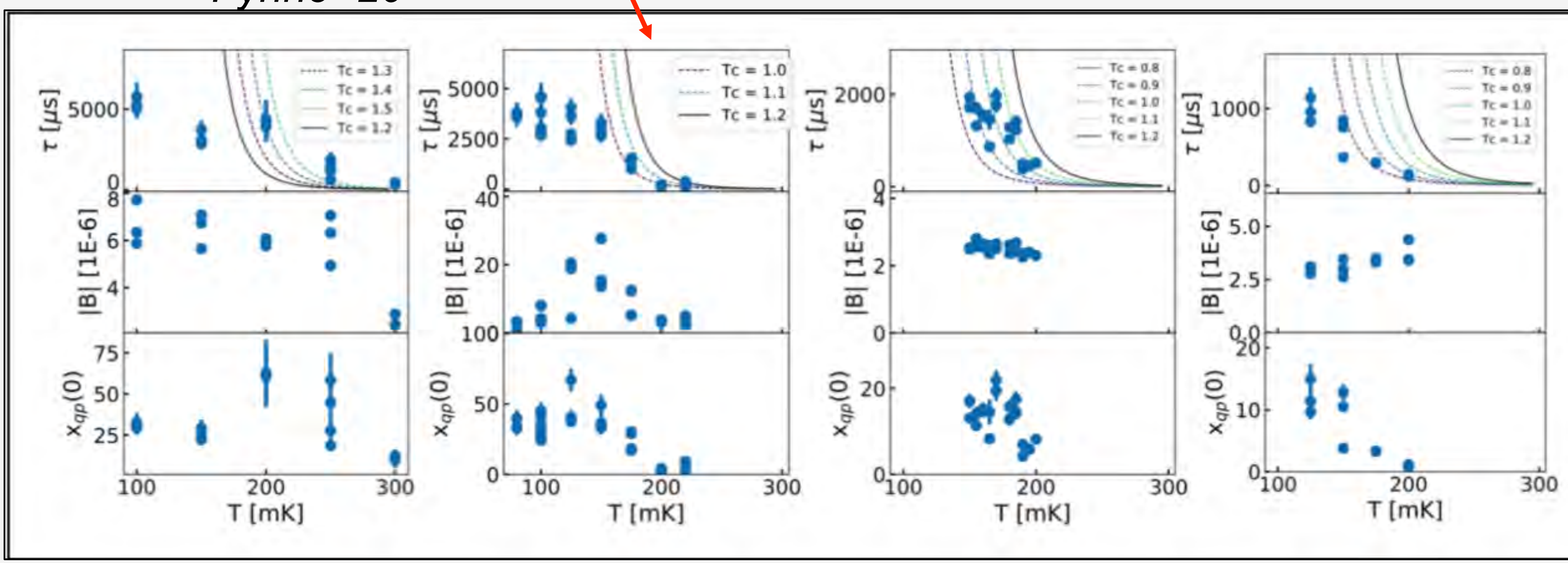
Quasiparticle Lifetime Measurements (Colorado/JPL)



- Measure **maxium τ_{qp} > 1 ms** for T < 150 mK

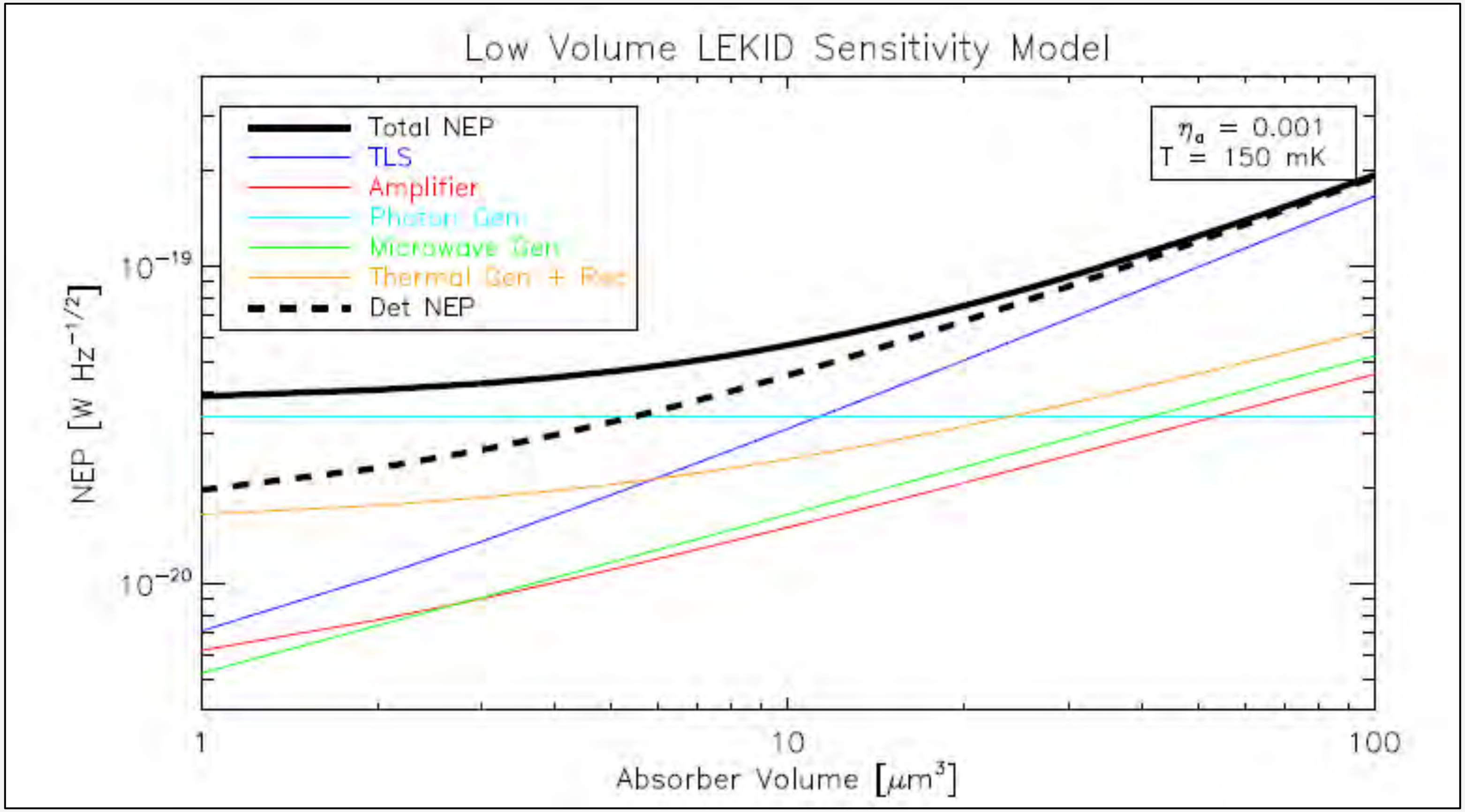


Fyhrie+20



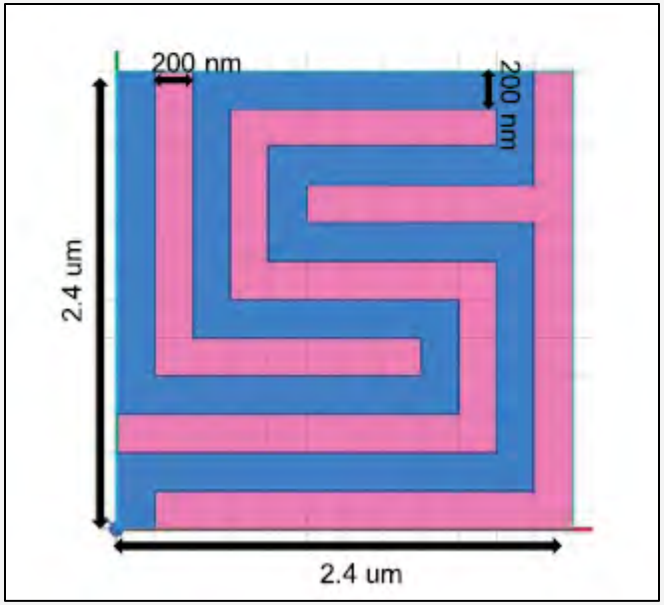
t = 20nm   t = 30nm   t = 40nm   t = 50nm

Reducing the NEP

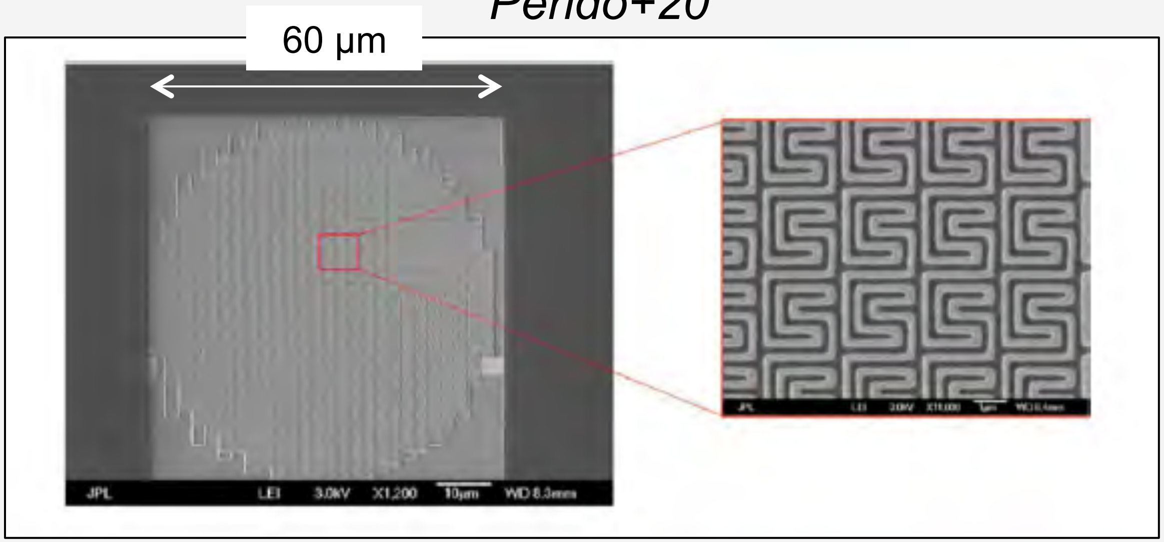


Hailey-Dunsheath+, submitted

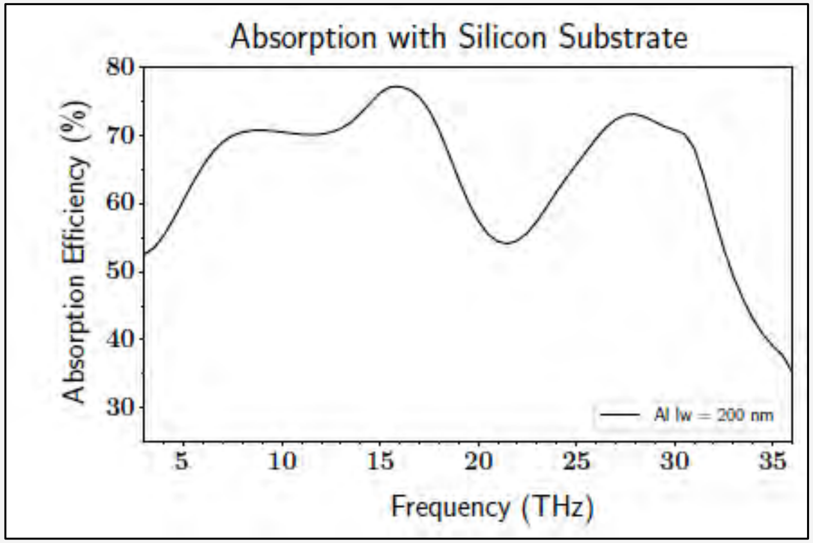
A 10 μm Absorber (U. Colorado / JPL)



Perido+20



- Backside illuminated
- Vertical polarization sensitive
- Absorber line interrupted with long meander to increase the resistance per unit length
- Pitch is 0.4mm
- Single-mode waveguide not possible at λ < 150 μm, coupling through multi-mode waveguide or microlens



See talk by Jason Glenn on Tuesday

Summary

Parameter	SOFIA Requirements	TIM KIDs	10 µm prototype KIDs
Operating Temp [mK]		< 250 (requirement) 150 (goal)	< 250 (requirement) 150 (goal)
Wavelength [µm]	40 – 215	350	10
Optical Coupling		Single-mode waveguide $\lambda > 150$ µm Multi-mode waveguide or microlenses at $\lambda < 150$ µm	microlenses
NEP [W/√Hz]	3×10^{-17} ($R = 10^3$) 3×10^{-18} ($R = 10^5$)	4×10^{-18} (demonstrated) $<1 \times 10^{-19}$ projected (low volume, low temp, high τ_{qp})	~4×10^{-18} (electrical) $<1 \times 10^{-18}$ projected (low temp, high τ_{qp})
Quantum Efficiency	> 50%	~ 95% dual-pol, single-mode waveguide over 30% band (simulated)	
Pitch [mm]	0.5	2.3	0.4
Subarray pixel count		~1,000	~1,000
Total pixel count	~10,000	x2 arrays totaling ~7,000	