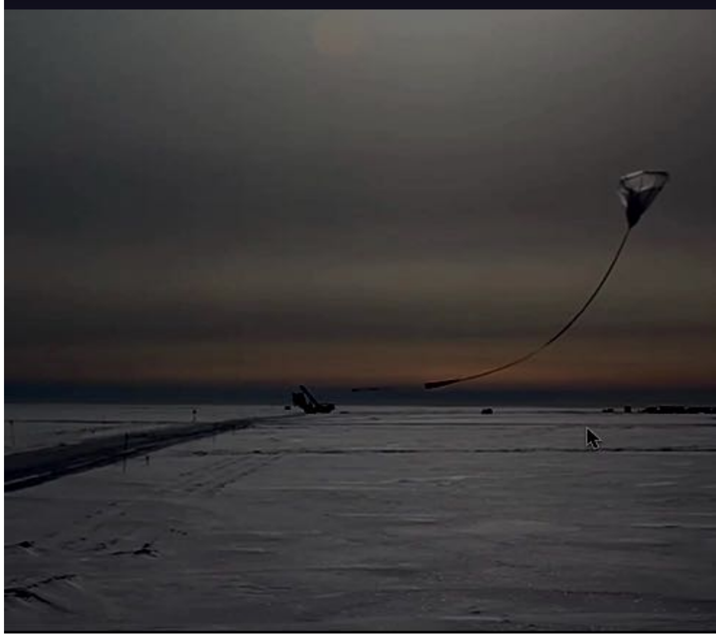
Ti/TiN Multilayer Kinetic Inductance Detectors for Sub-Millimeter and Millimeter-Wave Polarimetry

Jason Austermann

On behalf of **NIST-Boulder and BLAST** & **TOLTEC** Collaborations



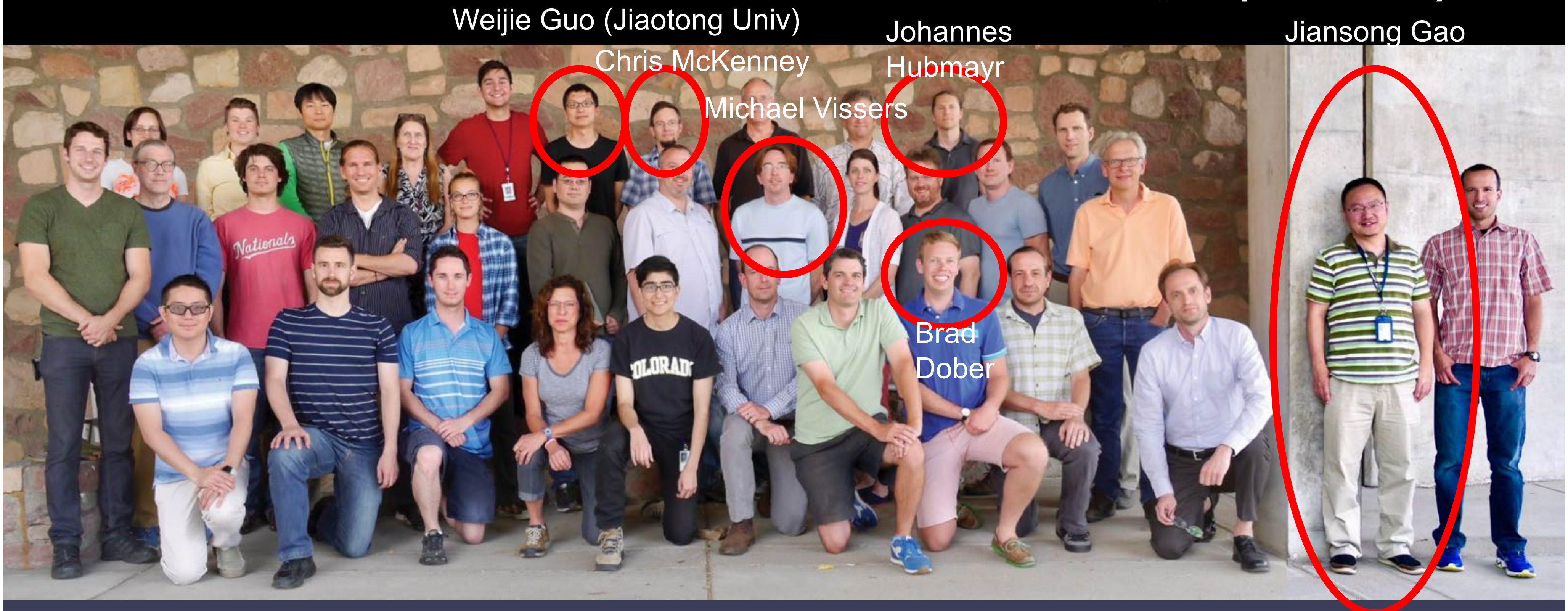
KIDs: The Next Generation Workshop

Dublin, Ireland;
8 Sept 2017

NIST Quantum Sensors Group (QSG)

- TES Calorimeters (X-ray, Gamma Ray)
- TES Bolometers (Sub-mm/mm detectors, polarimeters)
- Kinetic Inductance Detectors (KIDs)
- Readout (SQUIDS, Para amps, TDM/CDM, microwave squids, etc)
- Optics
- Cryogenics

NIST Quantum Sensors Group (QSG)



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- Optics
- Cryogenics

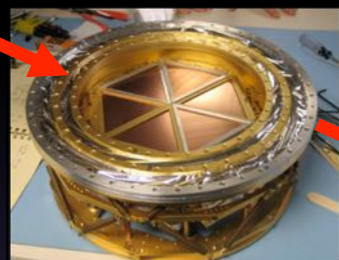
In collaboration with BLAST & Toltec collaborations

The Problem: Scalability is difficult
e.g. Cosmology

Gen 0:
$O(1)$ - $O(10)$
detectors

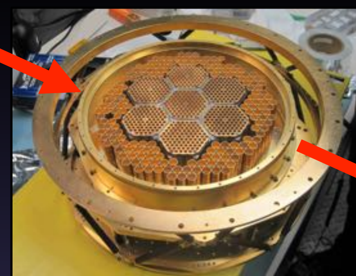
e.g. ACBAR
2001

Gen 1:
$O(100)$ – $O(10^3)$



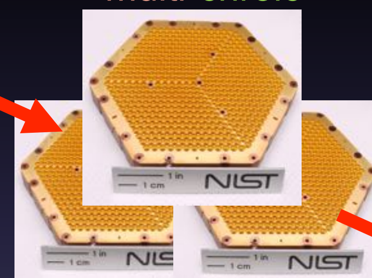
Examples:
SPT-SZ, MBAC
2007

Gen 2:
$O(10^3)$ +
polarization



Examples: SPTpol,
ACTPol, Polarbear
~ 2012

Gen 3:
$O(10^4)$ +
multi-chroic



e.g. Adv ACTPol
SPT-3G, PB-2
2016+

Gen 4:
$O(10^5)$ +
Multiple telescopes
& scales

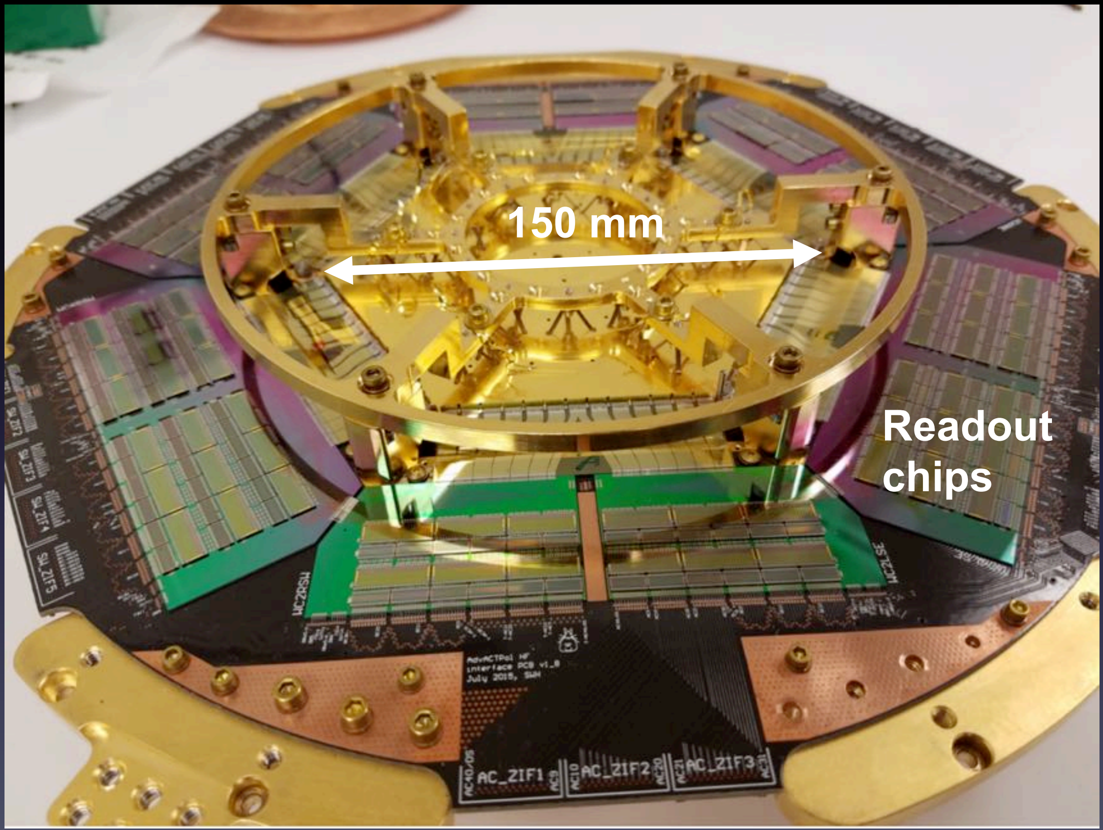
Simons Obs,
CMB-StageIV
2020+

All ~background-limited, therefore sensitivity gains come from:

- More Photons: more detectors, more bandwidth
- Added capability (polarization, spectral coverage)
- Control of systematics

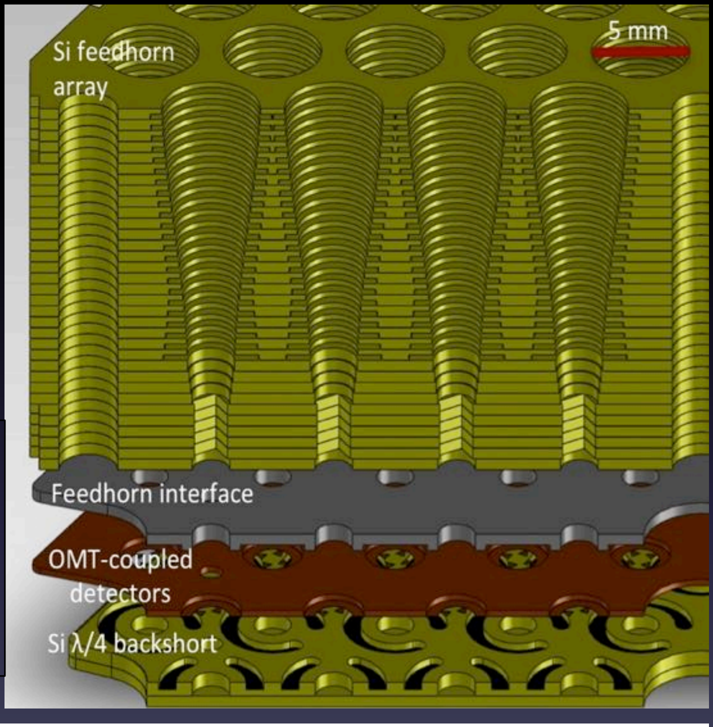
Scaled TES solution has grown in complexity

Advanced ACTPol HF Focal plane and cold readout components

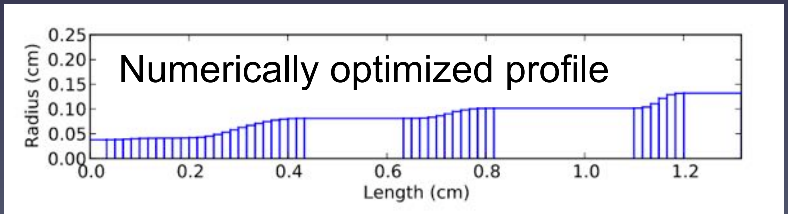


- Effort in assembly due to complexity has grown comparable to fabrication
- Thousands of wire bonds per array
- Multiple possible points of failure taking significant hit on yield
- KIDs could provide a truly scalable solution in the critical areas of fabrication, readout, yield, and assembly.
  - Integrated readout for TES is under development, but lags far behind KIDs inherent integrated readout

Silicon Platelet Feedhorn-Coupled Arrays



Yoon et al. *AIP* 2009
Hubmayr et al. *JLTP* 2012



Why Si Platelet Feedhorns?

Convenient & Flexible Design:

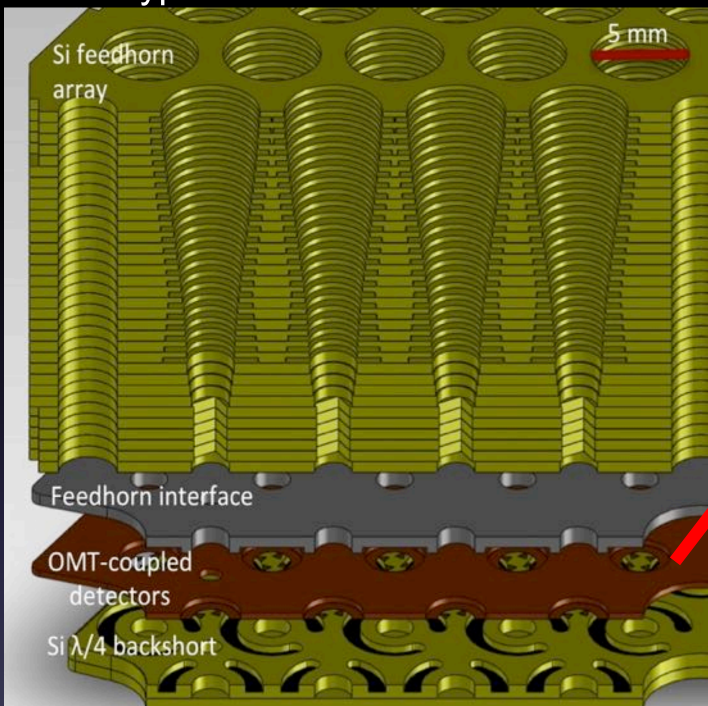
- Creates area for detectors/wiring
- CTE matched to Si detector wafer
- Planar interface (e.g. filtering)
- Flexible optical design for matching telescope
- Frequency Scalable

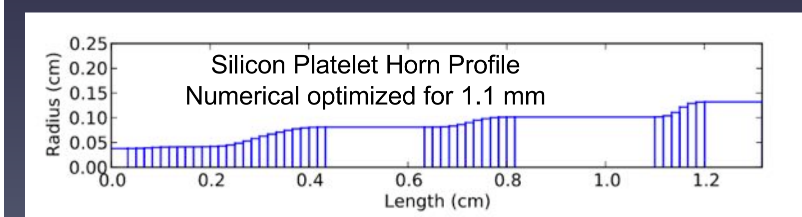
Low Systematics

- Near Gaussian beams
- Symmetric beams (inc. polarization)
- Micromachining results in nearly identical horns
- No AR coating required
- Waveguide high-pass & Natural RF shielding
- Low cross section to stray light

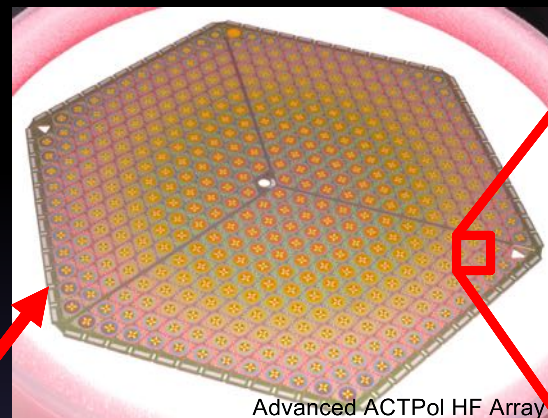
Typical NIST Feedhorn-Coupled Solution

Typical NIST Detector Stack

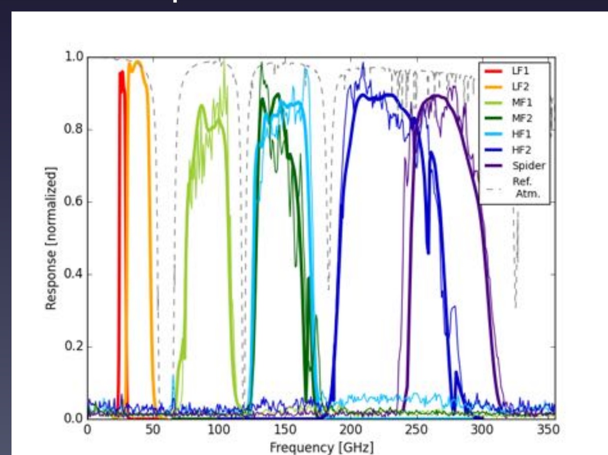




150-mm wafer production



On-chip multi-chroic solutions

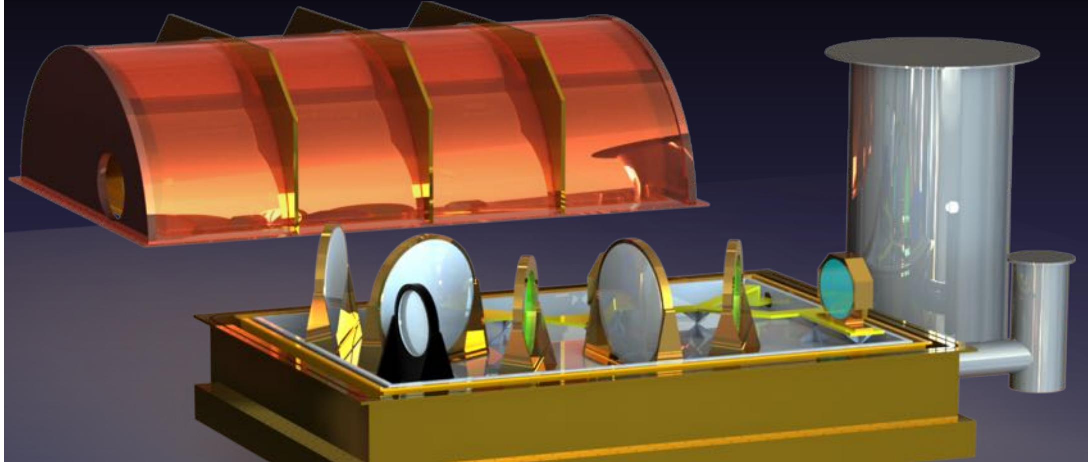


OMT coupled

Advanced ACTPol prototype

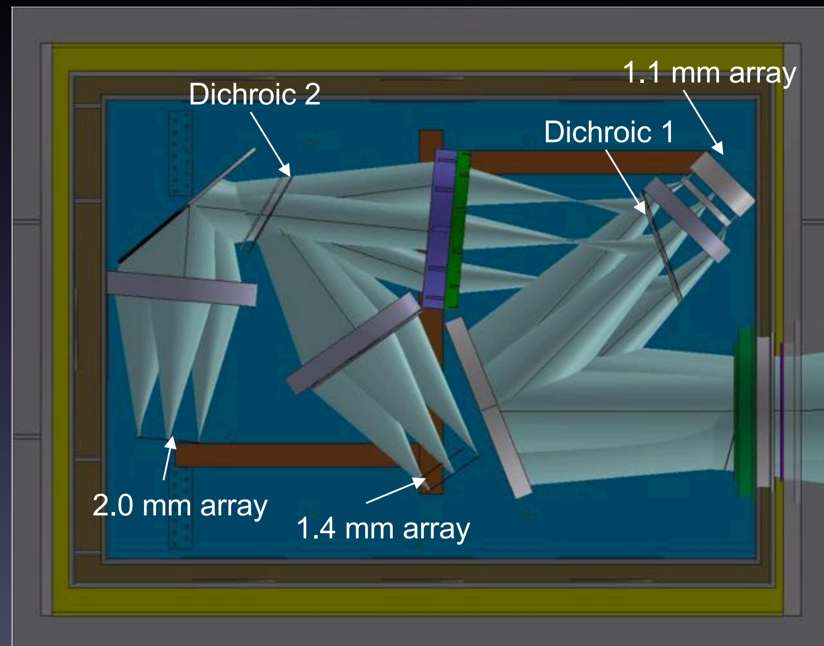
Current KID Projects: Dichroic filters define 3 frequency-independent focal planes

Toltec 4K optics concept



(only 1 focal plane shown for simplicity)

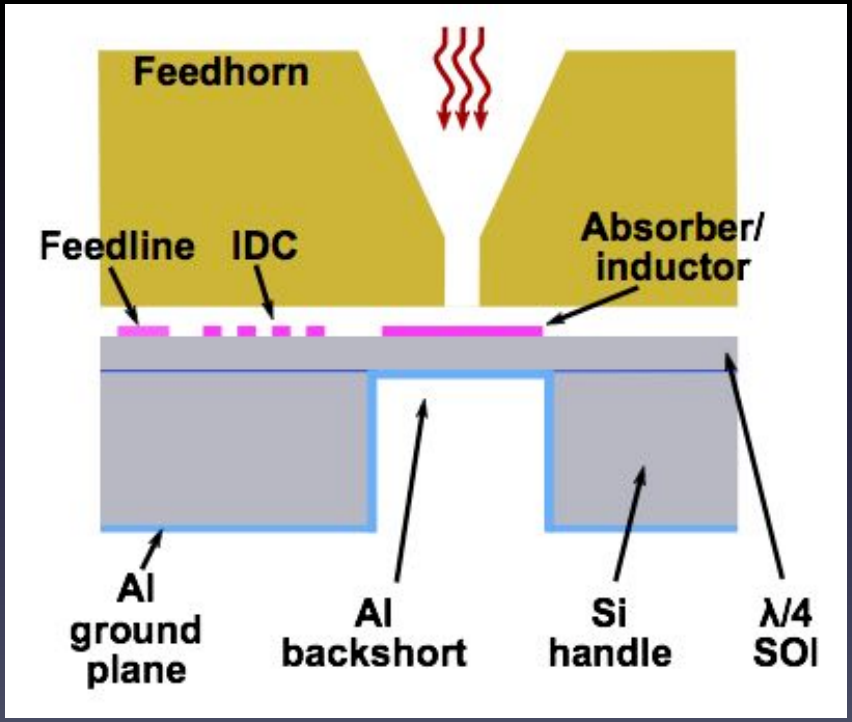
Toltec 4K optics top view



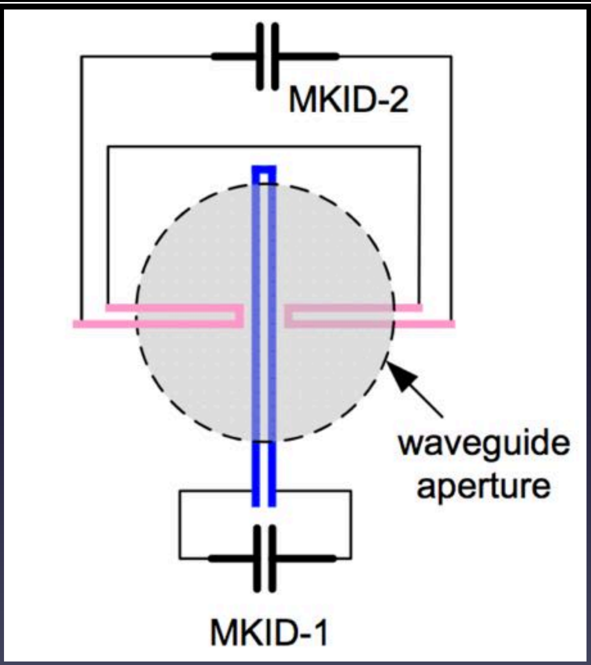
Optics design by Phil Mauskopf (ASU)

Fabrication Simplification: Direct Absorber

Cross-section



Direct absorber solution:
Effectively single-layer fabrication process



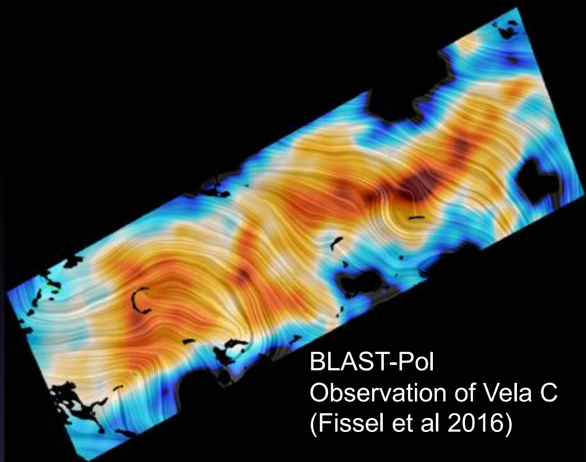
BLAST-TNG

- **High-Altitude Balloon telescope, 2.5-meter primary**
- ~ 3,500 polarization sensitive KIDs
- Roach2 Multiplexed Readout (ASU)
  - 1 MHz channel spacing, 500 MHz bandwidth
- Bath Temperature: **275mK**
- Expected Flight: **Dec 2018**
- 3 bands (micron): **250 350 500**
- Beamsize (arcsec): **25 35 50**
- Stepped Half Wave Plate
- Strength: Sub-mm polarimetry in hard to access wave bands

TOLTEC

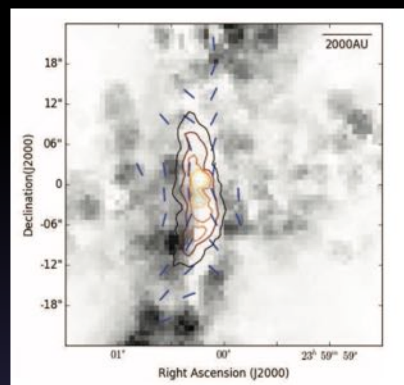
- 50-meter diameter Large Millimeter Telescope (LMT)
- ~ 7,000 polarization sensitive KIDs
- Roach2 Multiplexed Readout (ASU)
  - 1 MHz channel spacing, 500 MHz bandwidth
- Bath Temperature: **100 mK**
- Expected first light: **Dec 2018**
- 3 bands (micron): **1100 1400 2000**
- Beamsize (arcsec): **5.0 6.3 9.5**
- Continuously rotating Half Wave Plate
- Strength: high mm-wave mapping speeds w/ high angular resolution

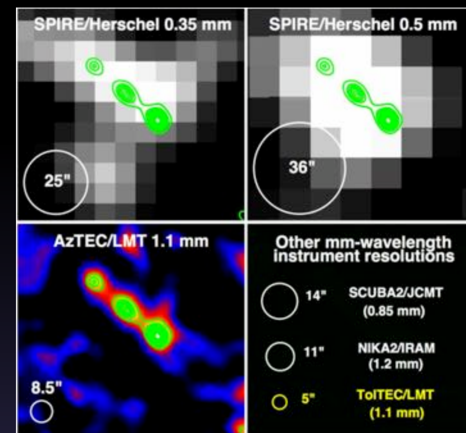
Wide ranging science applications



BLAST-Pol
Observation of Vela C
(Fissel et al 2016)

Simulated Toltec obs of protostellar region

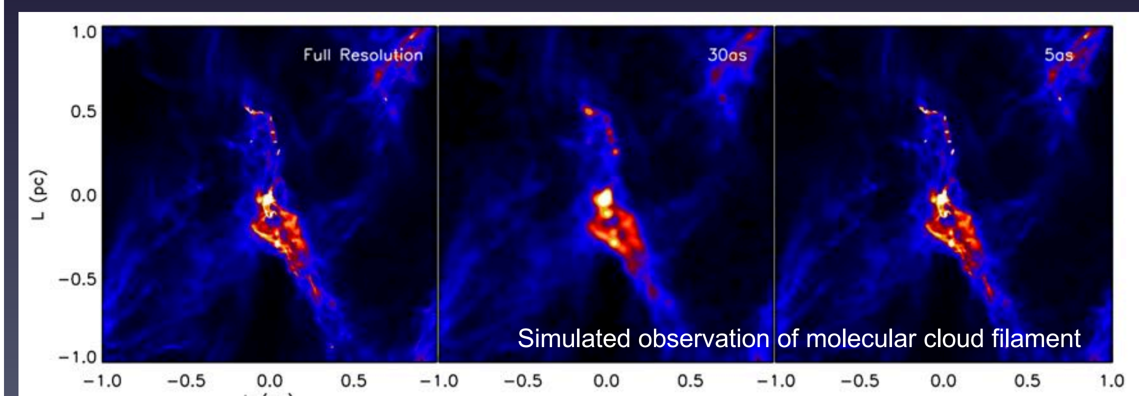




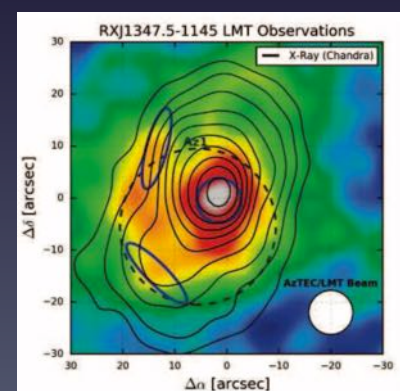
High-redshift
star-forming
galaxies

Star Formation, Molecular clouds

Extragalactic/Cosmology

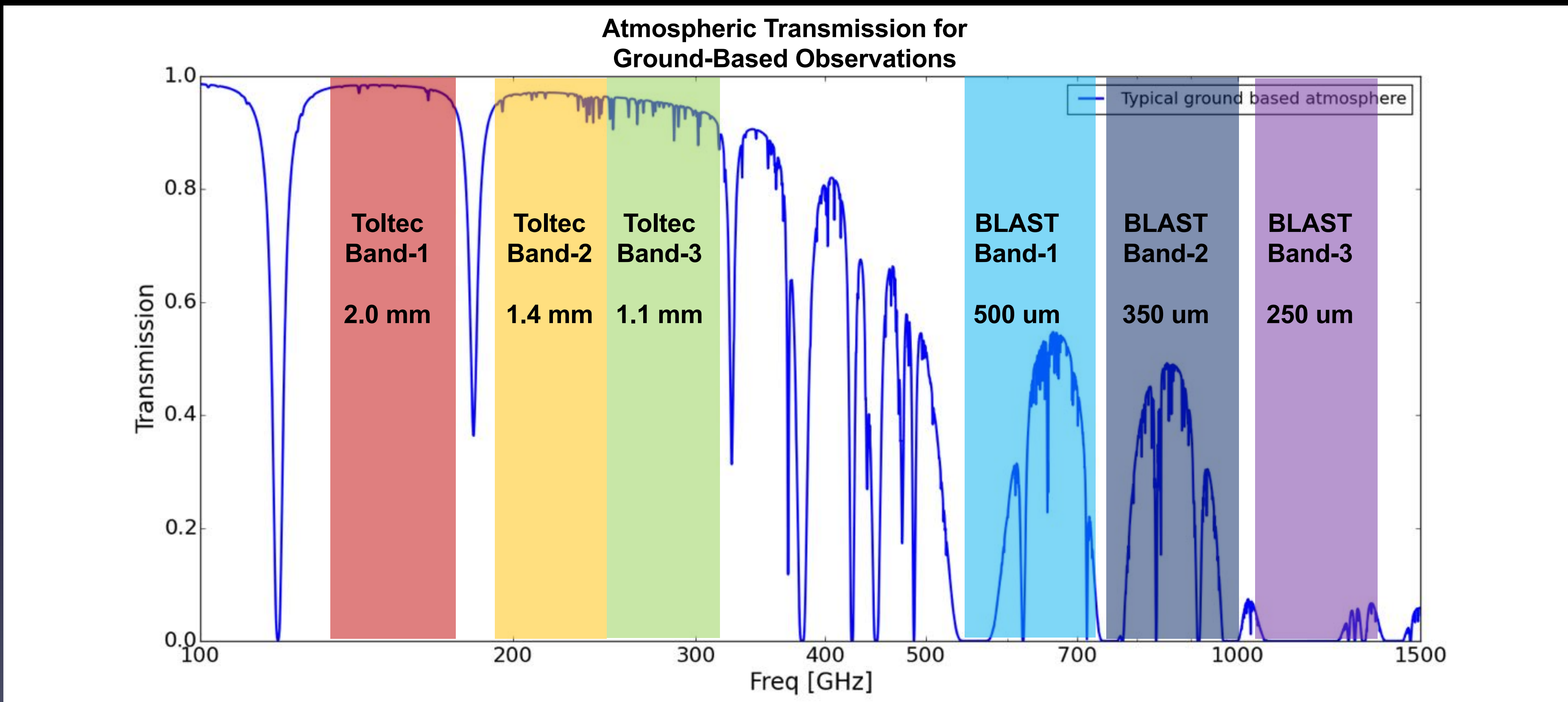


Simulated observation of molecular cloud filament



AzTEC/LMT
observation
(color) of SZ
cluster

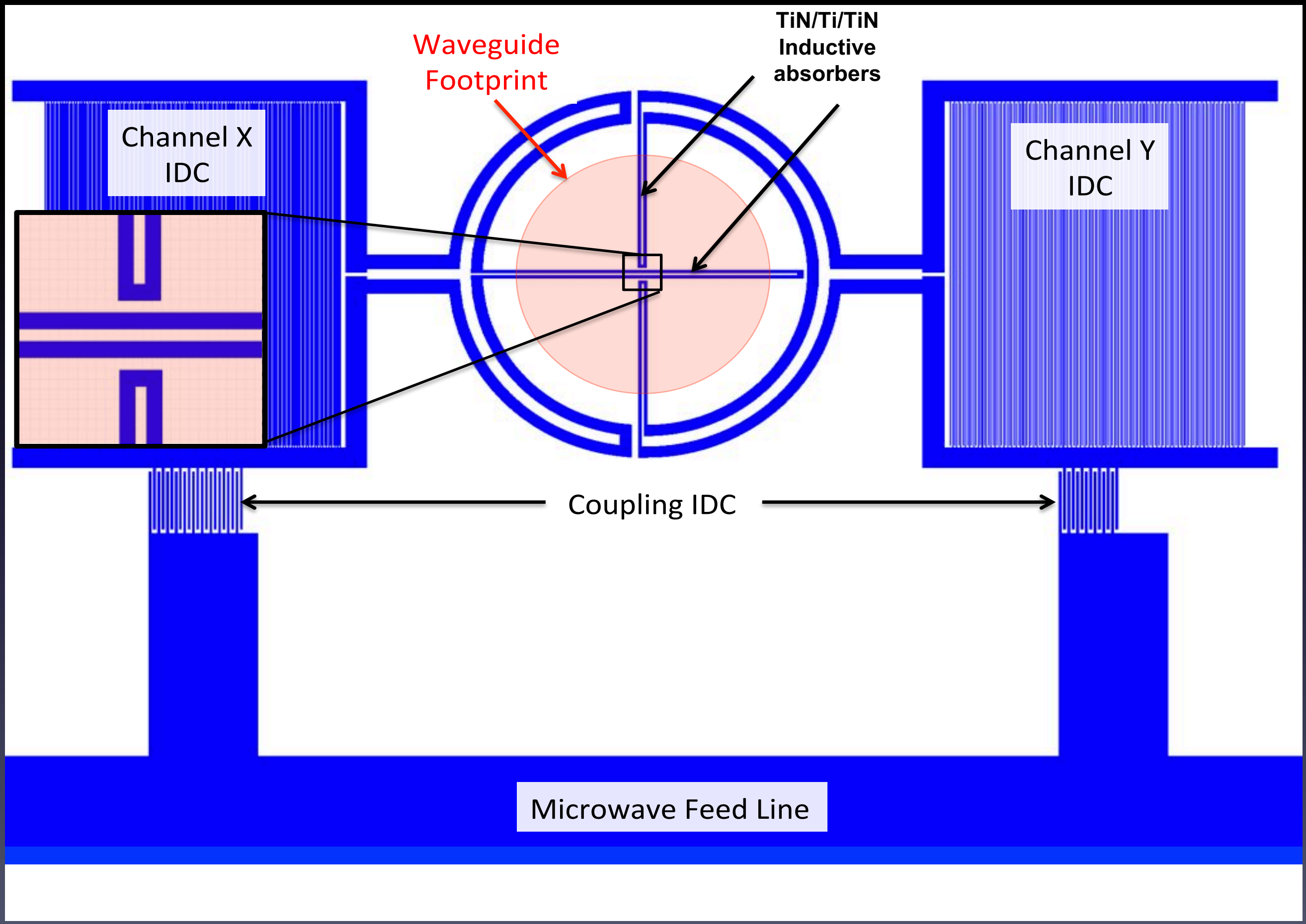
Order of magnitude frequency coverage



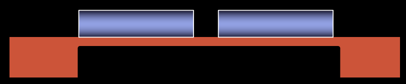
CSO atmospheric model, 0.5 PMV

Pixel Architecture

Direct absorber solution:
Simple Fabrication

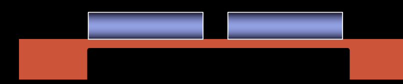


Material: TiN/Ti/TiN Multi-Layer



Material advantages:

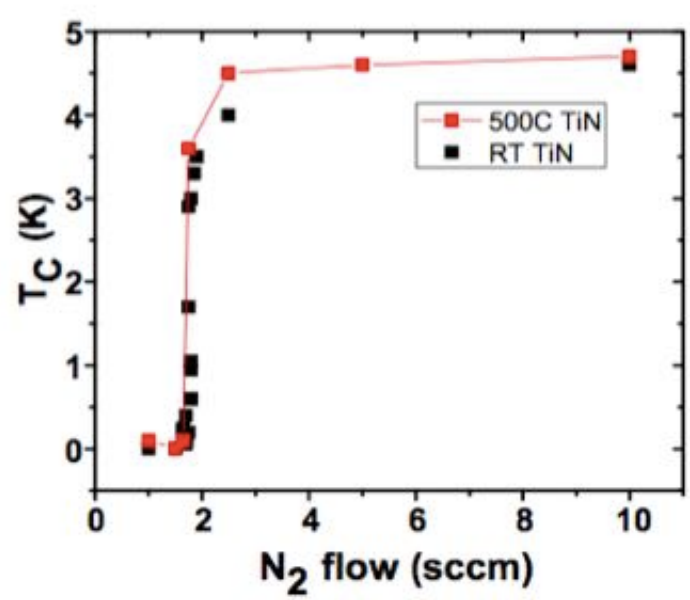
Material: TiN/Ti/TiN Multi-Layer



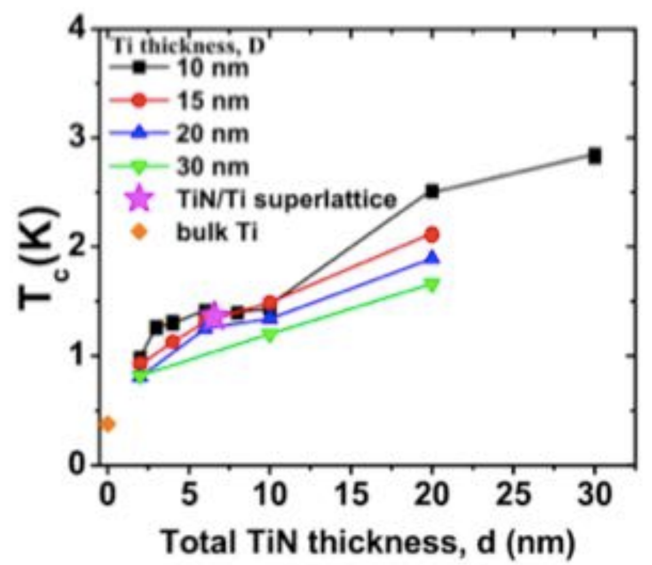
Material advantages:

- Tunable T_c
  - Tune to experiment bath temperature and photon energy

TiN only



TiN/Ti/TiN
Trilayer



Vissers et al. 2013

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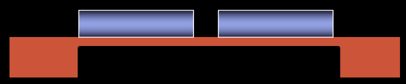
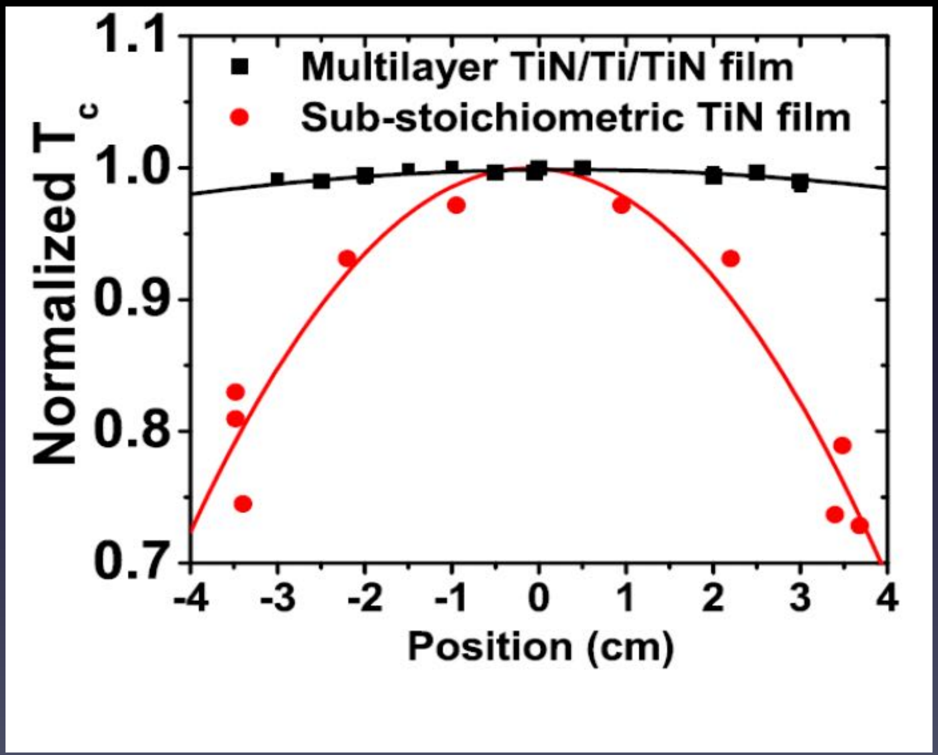


Material advantages:

- Tunable T_c
  - Tune to experiment bath temperature and photon energy
- T_c uniformity

Trilayer T_c uniformity



Vissers et al. 2013

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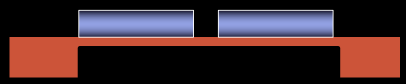
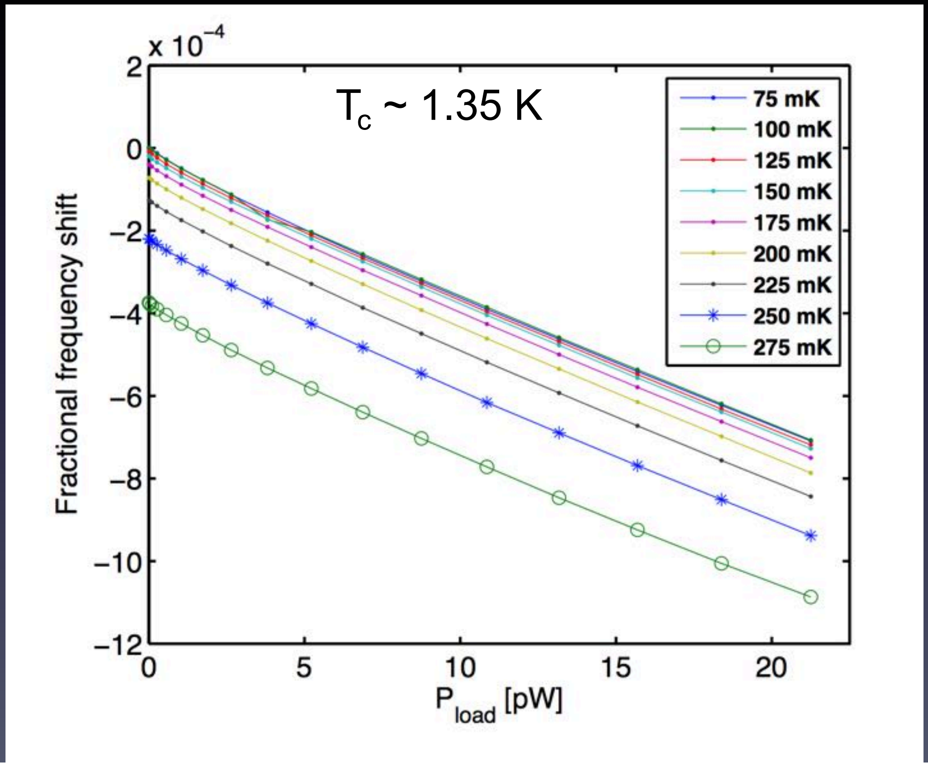


Material advantages:

- Tunable T_c
  - Tune to experiment bath temperature and photon energy
- T_c uniformity
- Linear response
- High kinetic inductance fraction

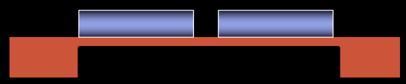
Good Responsivity

Linear response over wide range of optical powers and bath temperatures



Hubmyer et al 2015

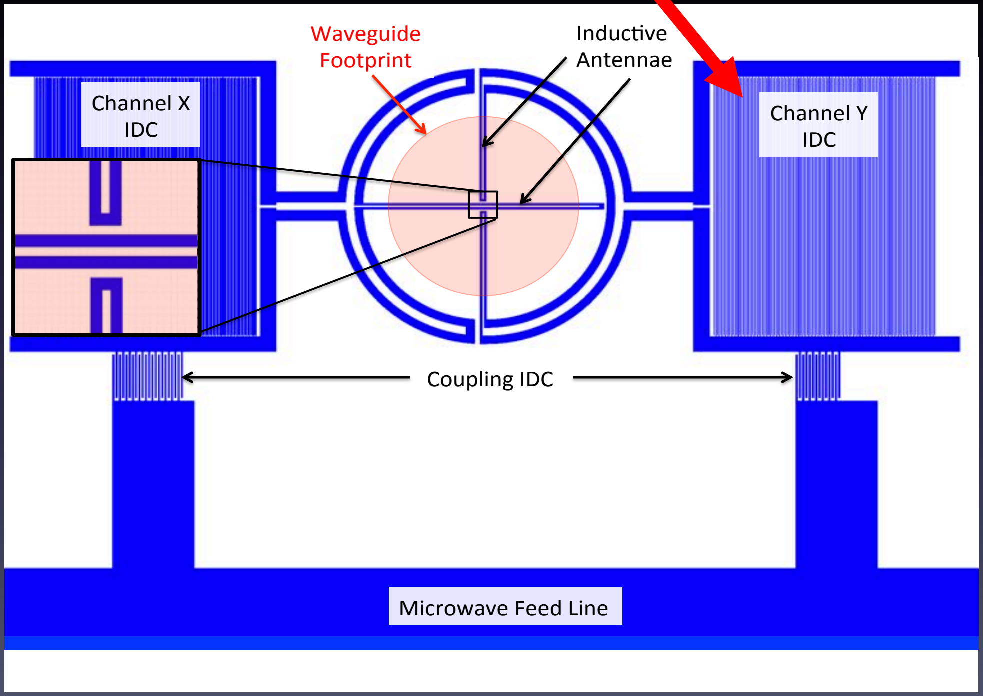
Material: TiN/Ti/TiN Multi-Layer



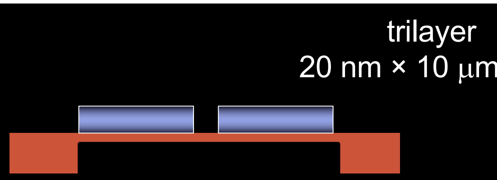
Low TLS allows us to make very compact capacitors (routinely built as 2um/2um)
→ allows for close packing of pixels

Material advantages:

- Tunable T_c
  - Tune to experiment bath temperature and photon energy
- T_c uniformity
- Linear response
- High kinetic inductance fraction
- Low TLS at TiN/Si interface

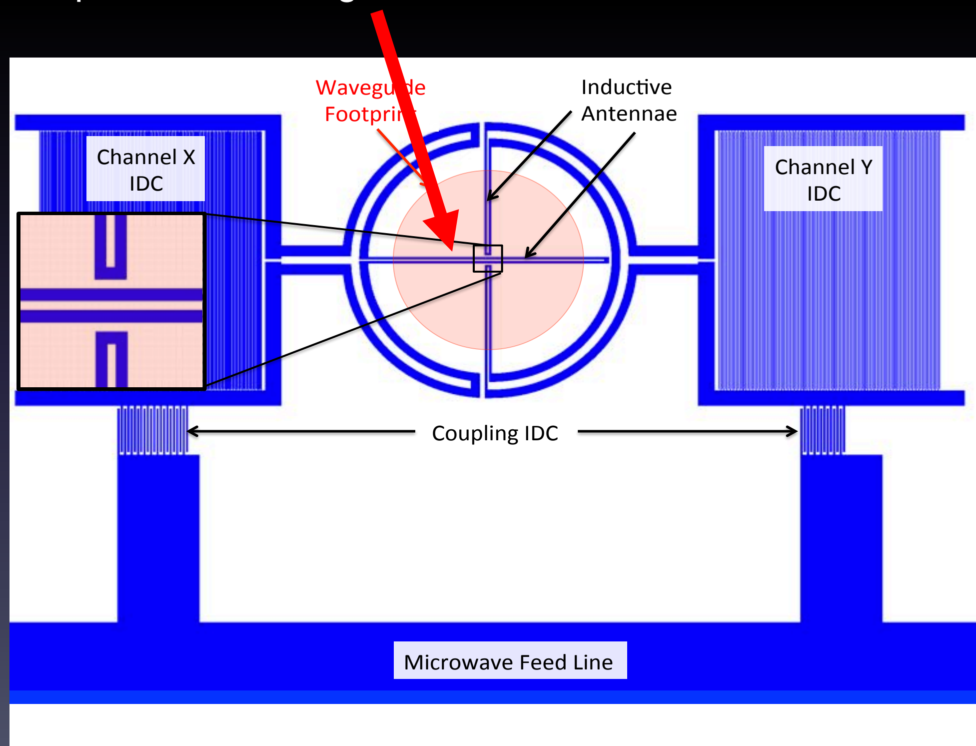


Material: TiN/Ti/TiN Multi-Layer



Material advantages:
- Tunable T_c
  - Tune to experiment bath temperature and photon energy
- T_c uniformity
- Linear response
- High kinetic inductance fraction
- Low TLS at TiN/Si interface
- High sheet resistance (tunable)

Allows Impedance matching to incoming radiation with simple to fabricate geometries



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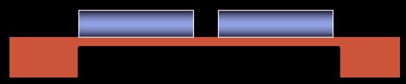

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- Linear response
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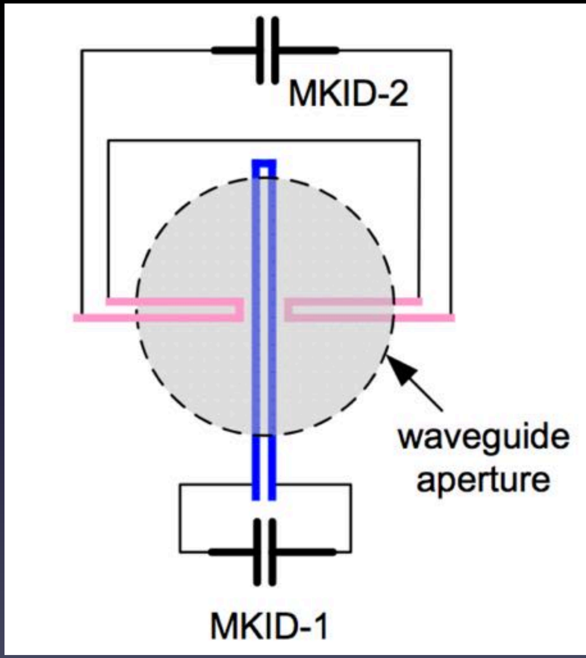
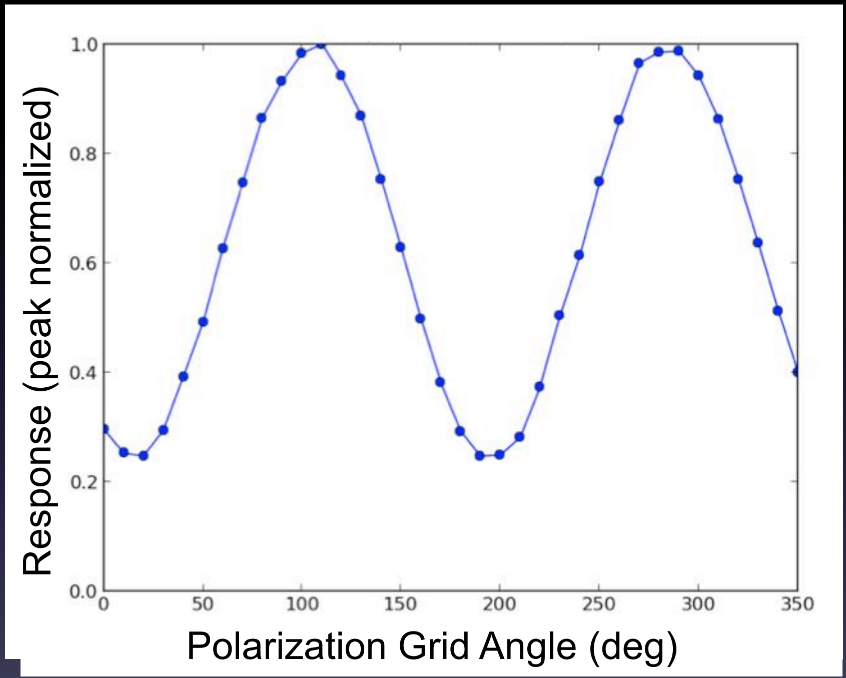
Need to balance:
- impedance matching
- material volume (responsivity)
- low cross-pol / high co-pol
- Transition Temperature

First Generation

Impedance and volume designed from first principles. w = 10 um

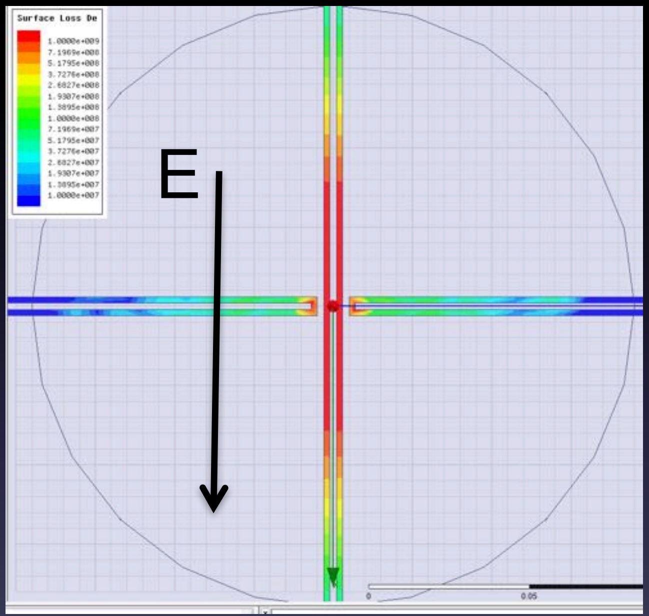


Large Cross-Polarization pickup



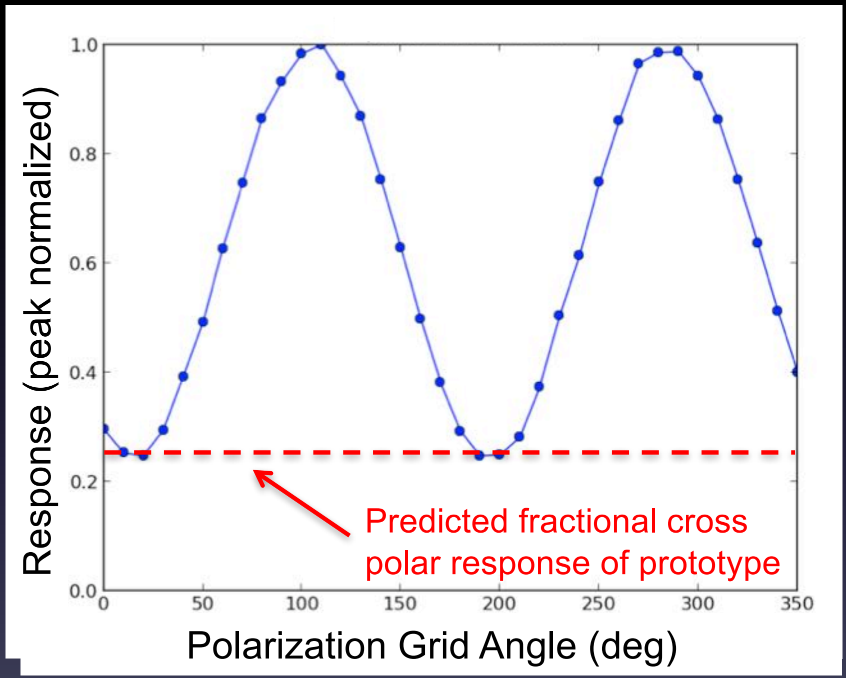
First go

Surface loss simulation



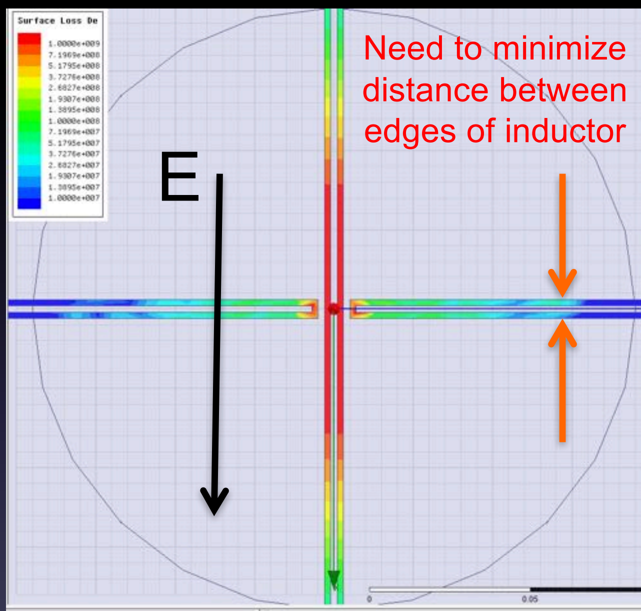
Cross-pol pickup as field induces current in orthogonal inductor

Polarization response matches simulations

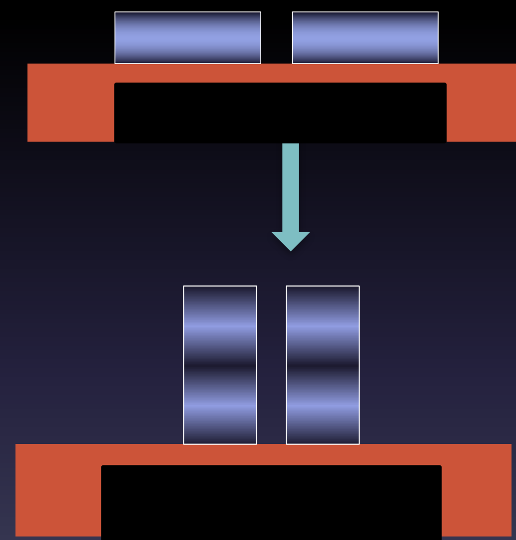


Cross-polarization

Need to thin inductor traces, but maintain impedance of line and desired volume



trilayer
20 nm × 10 µm

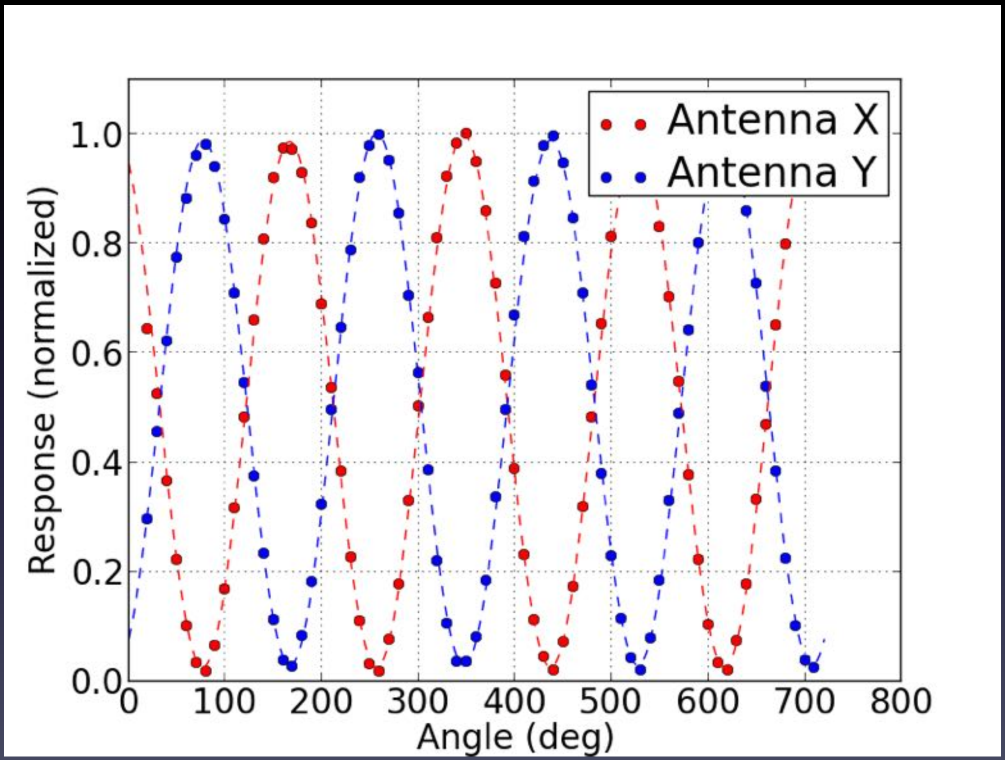


multilayer
80 nm × 2.5 µm

Same volume, ¼ impedance, ¼ width

Cross-polarization

Cross-pol ~2%, matching simulation



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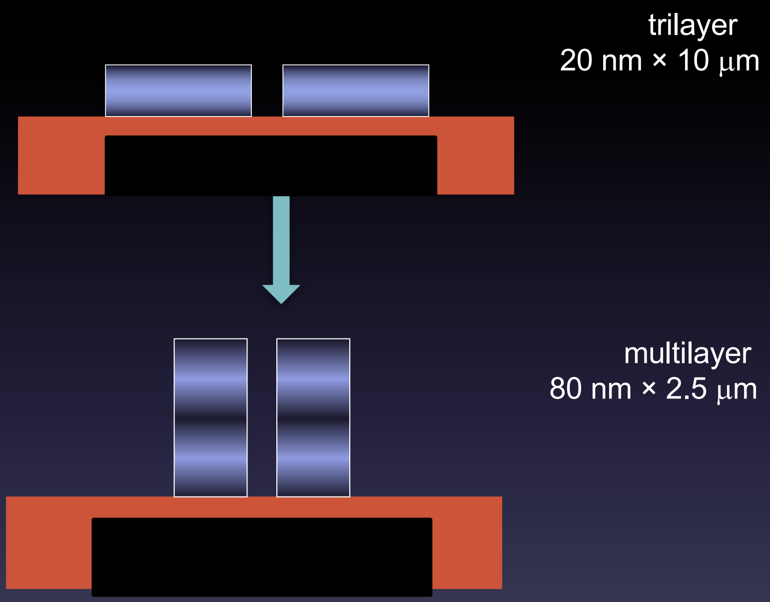
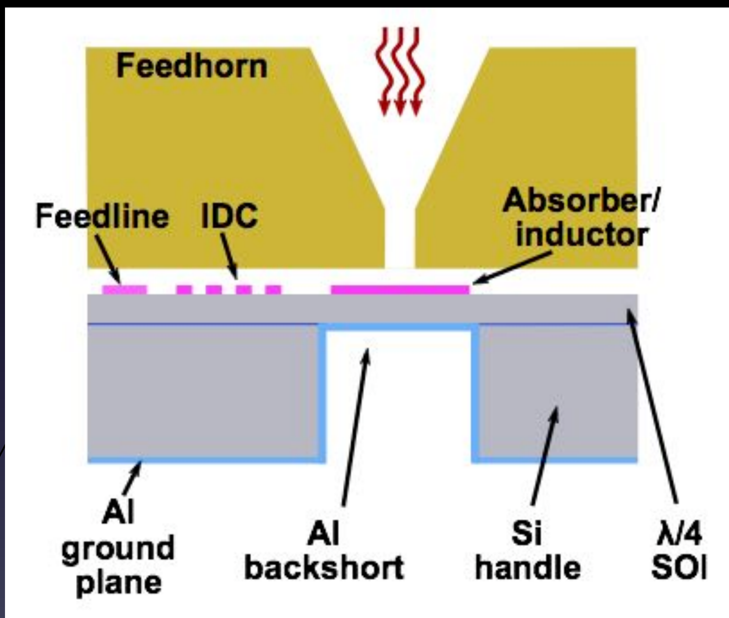


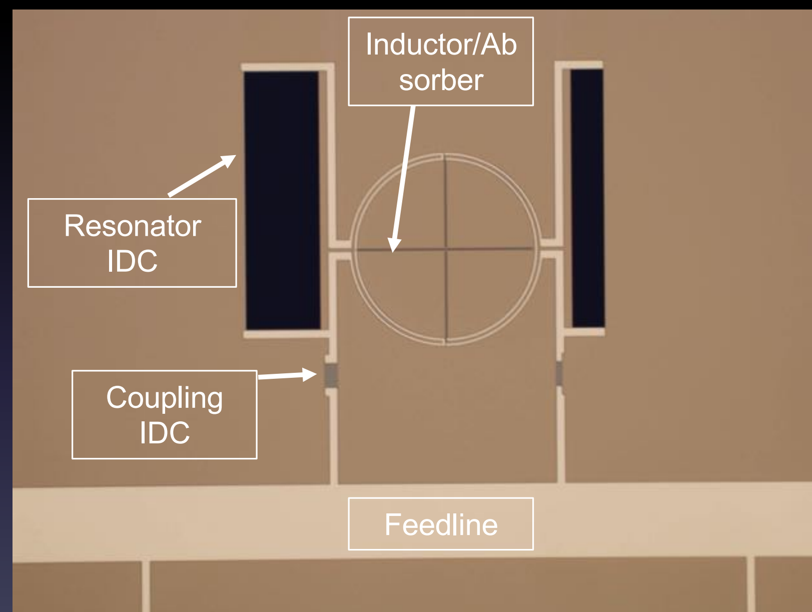
Same volume, ¼ impedance, ¼ width

Wavelength scalable solution… except volume also scales

Cross-section



Direct absorber solution:
Effectively single-layer fabrication process

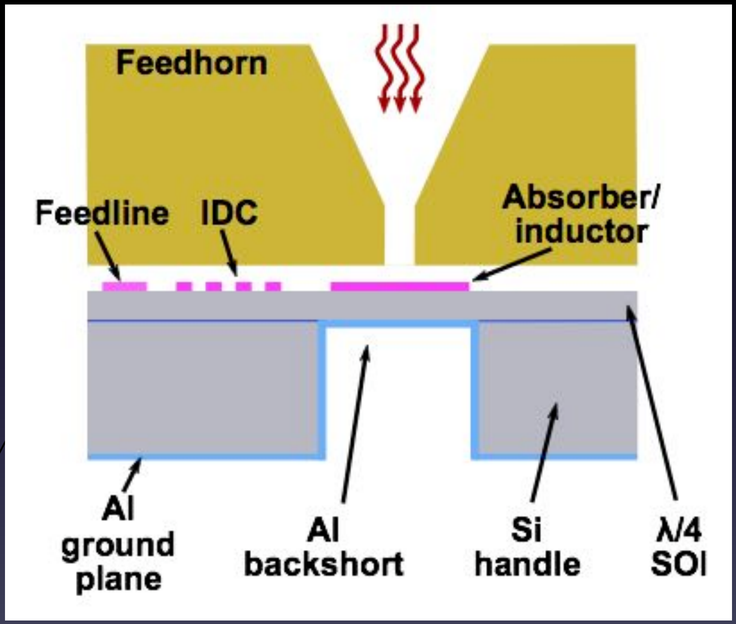


Toltec 1.1 mm band pixel

Additional tuning knob: shorting bars

Helps decouple volume, cross-pol, and impedance considerations

Cross-section



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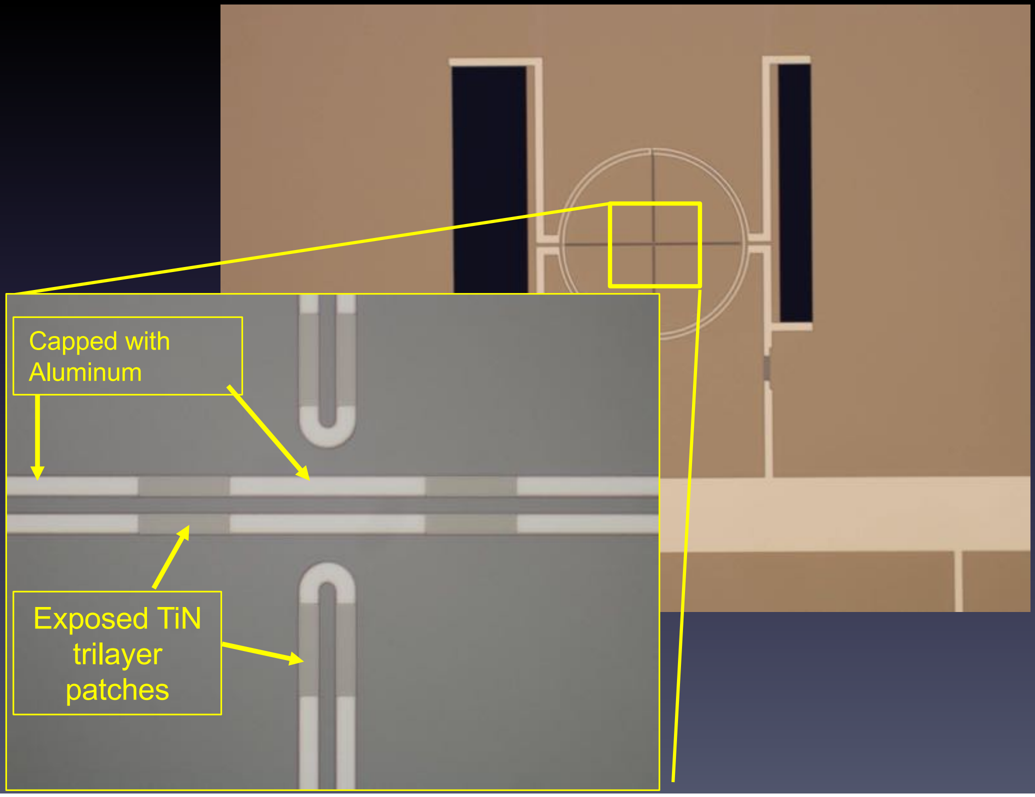
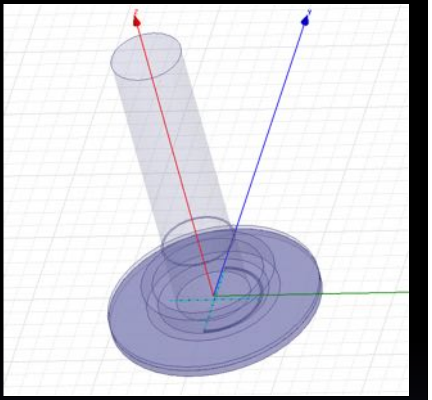
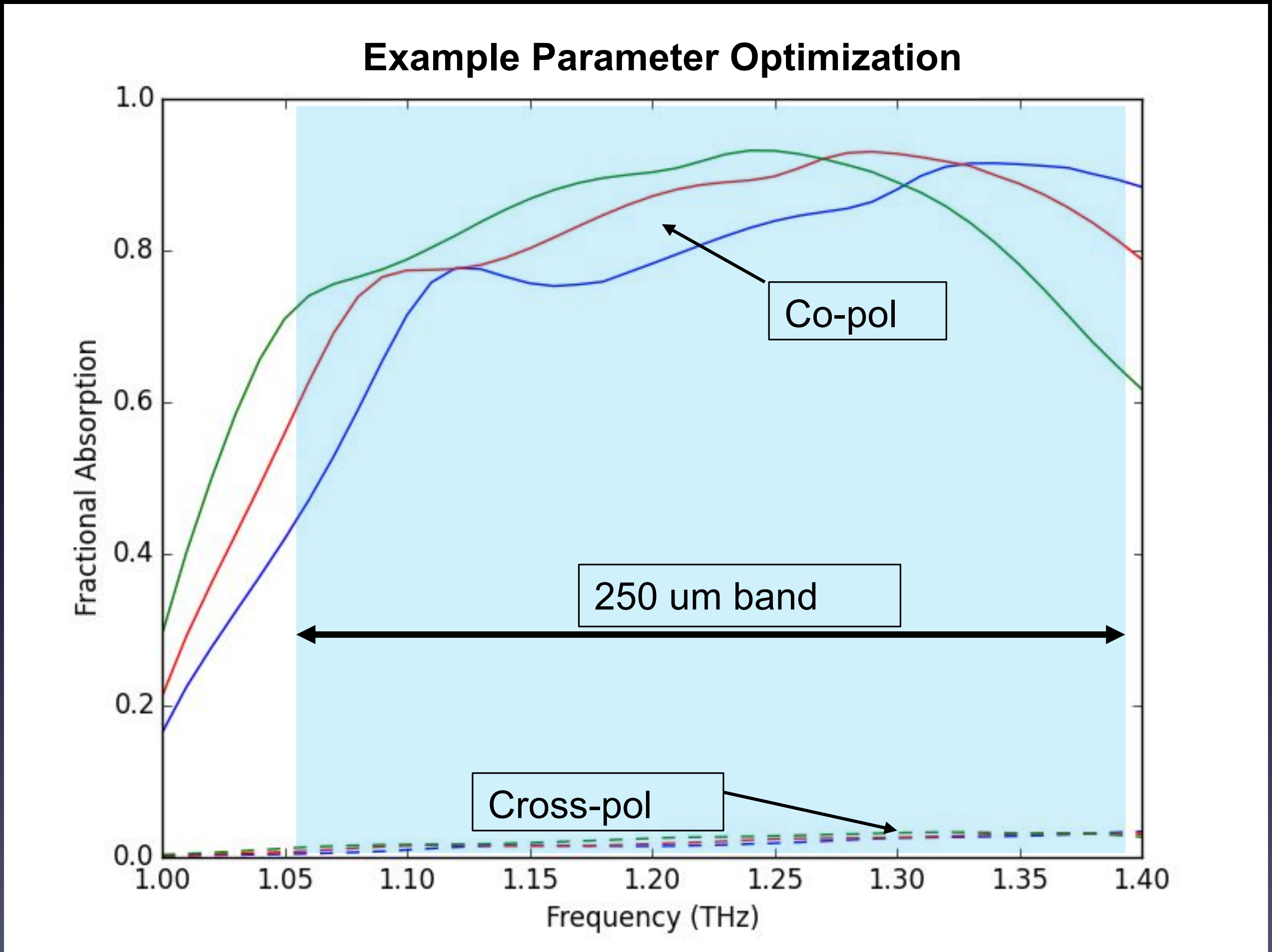


HFSS Optimization of Geometric Parameters



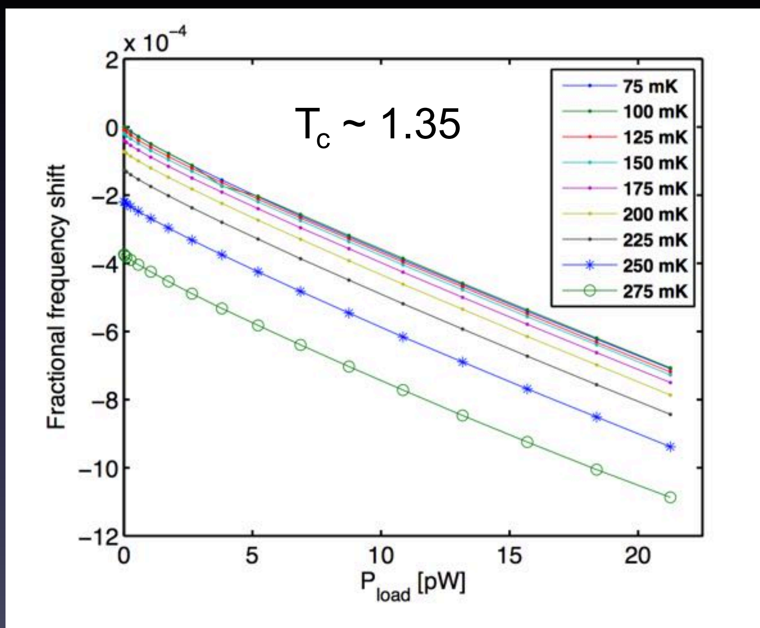


Extensive modeling in Ansys HFSS

- **Maximize in-band co-pol absorption.**
  - **Achieving 80—90% band averaged efficiency at experimental bandwidths**
- **Minimize cross-polarization pick up**

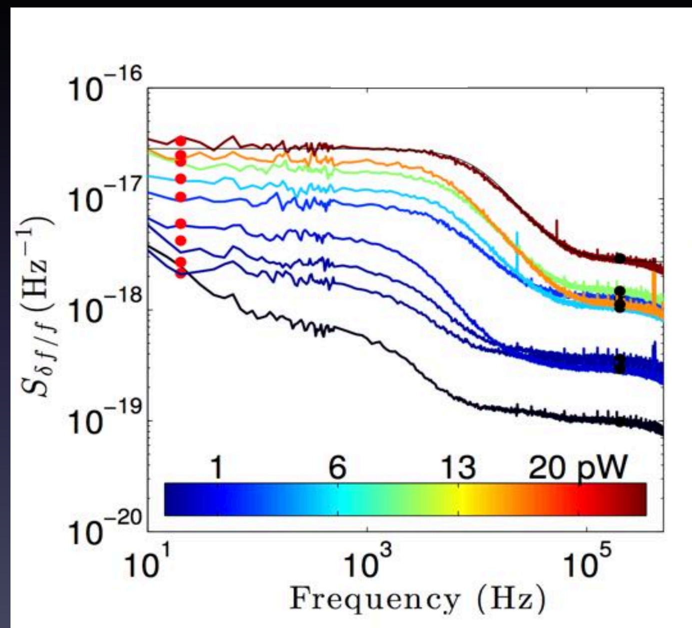
Measured Response and Noise at 250 μm

Linear response over wide range of optical powers and bath temperatures



Nearly constant slope represents a departure from conventional superconductors and results in enhanced responsivity

Noise as a function of optical loading power

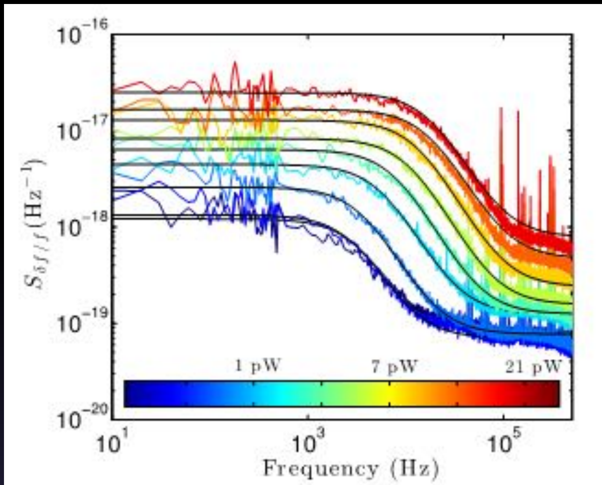


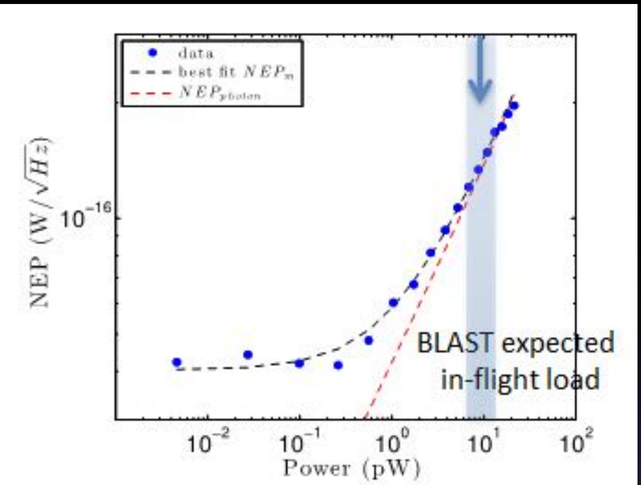
Hubmyer et al 2015

Measured Optical Performance

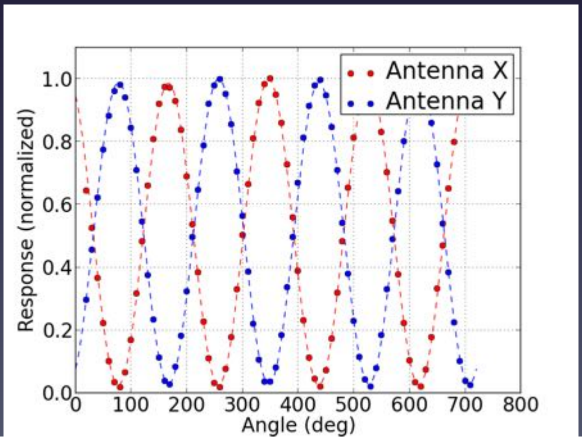
Photon-Noise Limited Performance (250um band)

Hubmayr et al, APL 106, 073505 (2015).

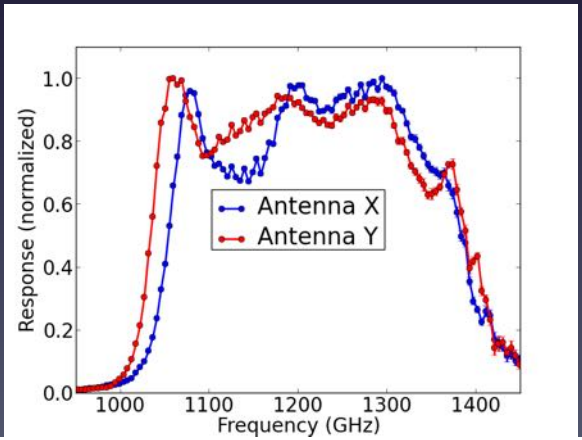




Excellent cross-pol rejection



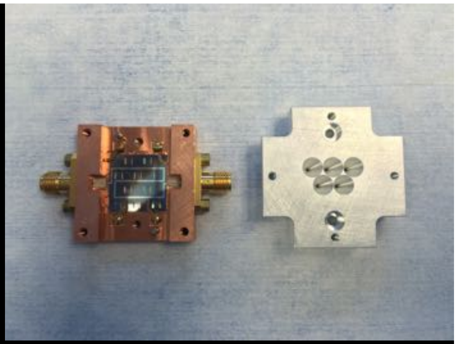
Good wide-band response



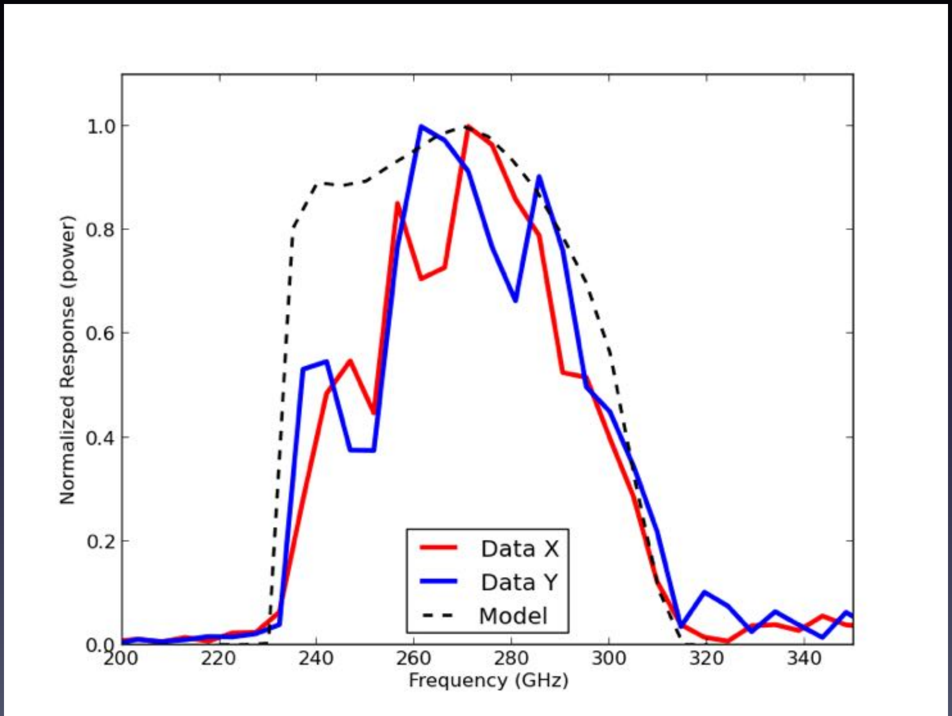
Polarization efficiency and frequency response match simulations and modeling

Cross pol < 2%

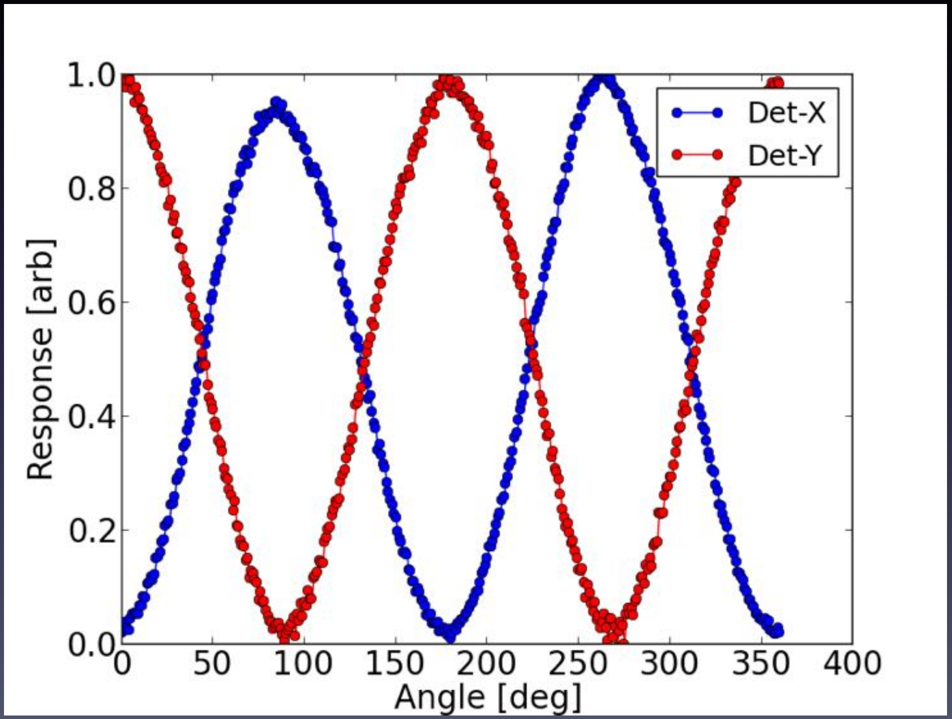
Prototype 1.1 mm polarimeters



Passband

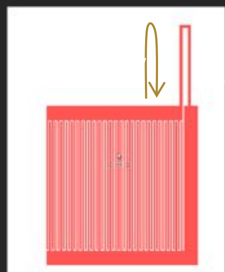


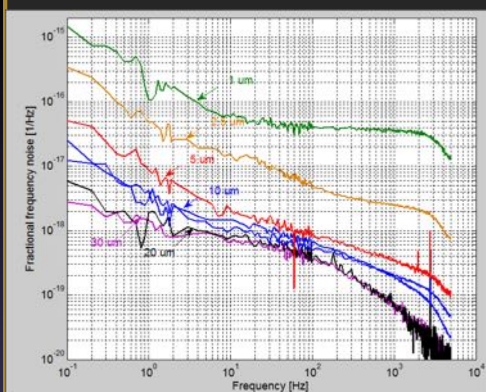
Cross-Pol ~< 2% (Matching Sims)



Noise Contributions

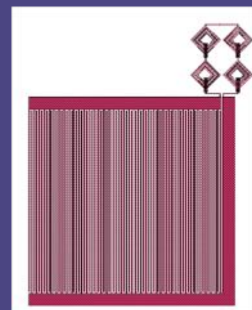
Inductor noise

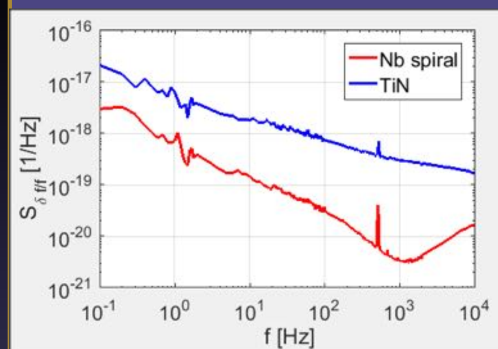




- No power, temperature dependence
- Not dependent on IDC capacitor
- Phase only noise.
- S ~ 1/w^2 when impedance matched (NEP wins out)
- Kinetic inductance fluctuations

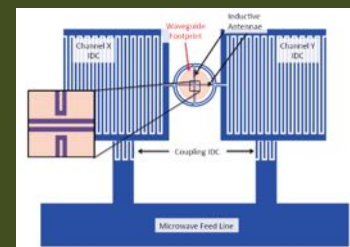
TLS noise in the capacitor

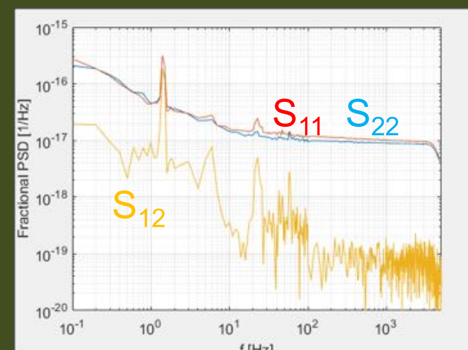




- Replacing TiN inductor with a Nb spiral inductor (no KI) noise reduced by a factor of 10.
- Phase only noise.
- Detector dark noise is dominated by inductor noise but not TLS noise.

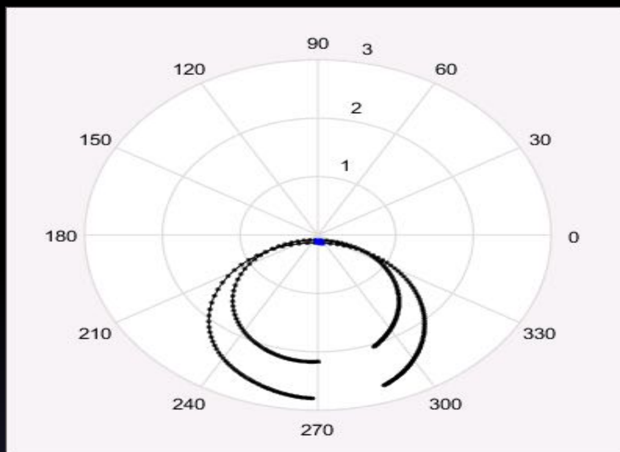
Excess 1/f qp noise under optical load

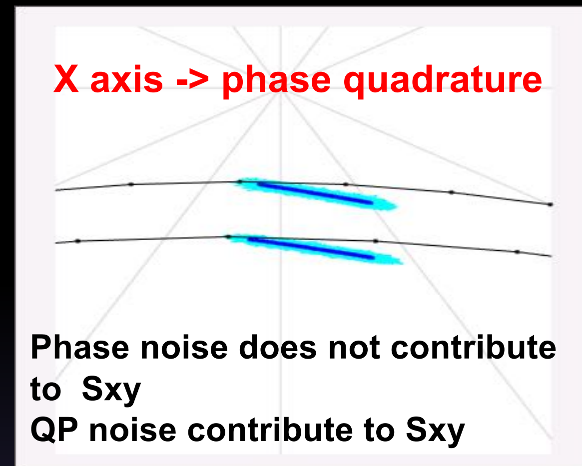


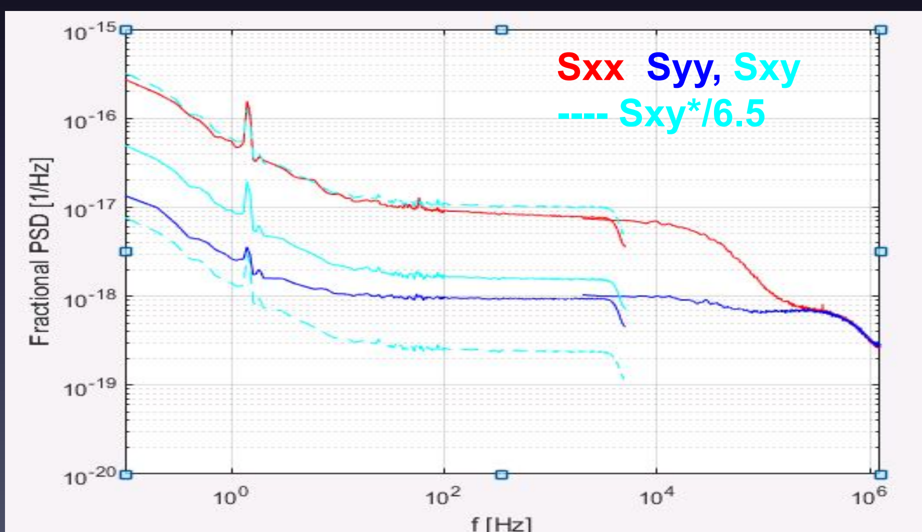


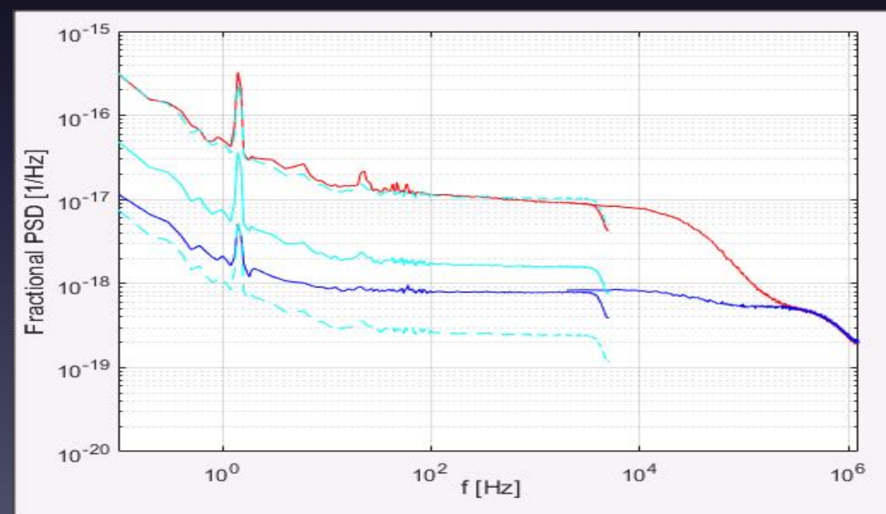
- Excess 1/f noise under loading uncorrelated between two resonators – not from blackbody fluctuation.
- 1/f knee at ~1-5 Hz
- Noise in the quasiparticle quadrature and is related to qp fluctuations.

1/f noise is in the QP system

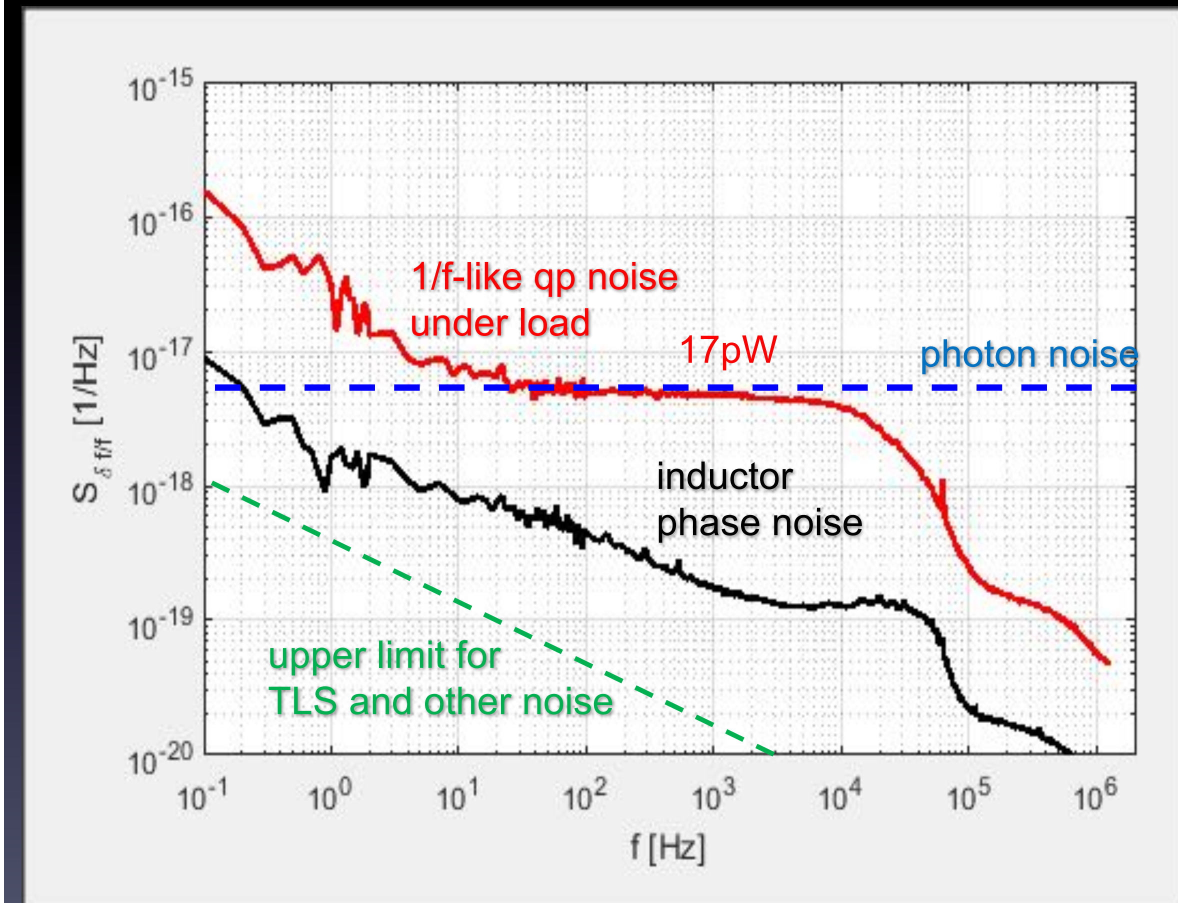








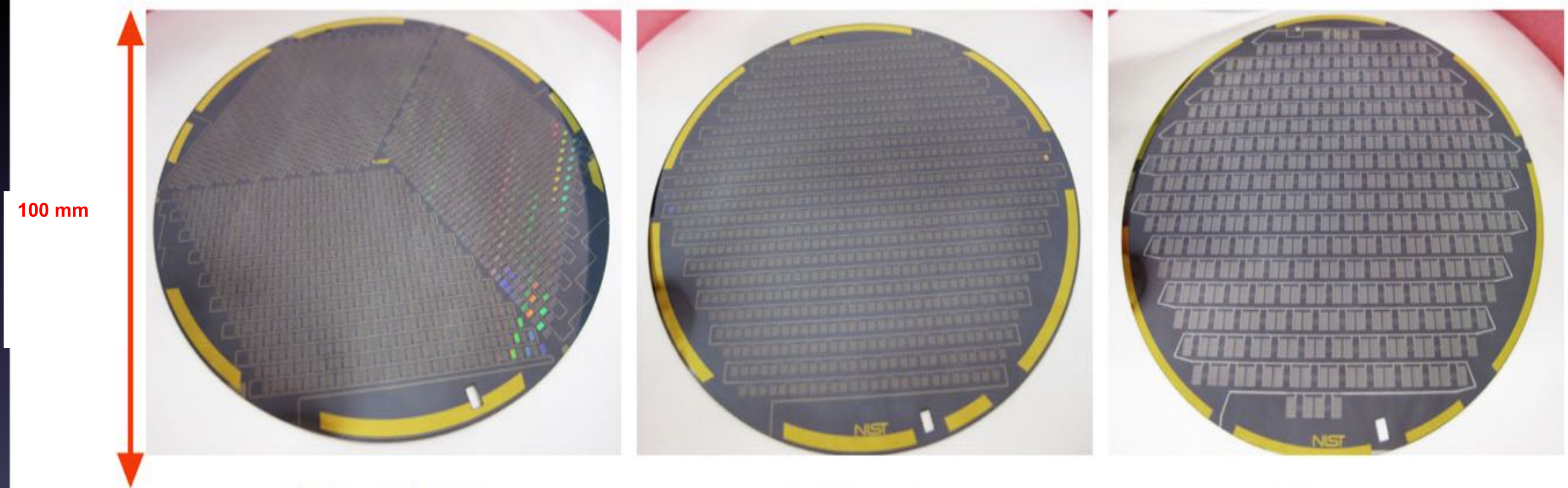
Detector Noise Contributions



- 1/f knee ~ 1 – 5 Hz
- In optically generated quasiparticle system, but not correlated between detectors
- Partially mitigated in current experiments
  - rotating HWP (for polarization observations),
  - observing strategy
  - Dominant atmospheric noise (for Toltec continuum date)
- Noise origin still under investigation
  - working on geometry and material solutions
  - Welcome experience from the TiN community

Large-Format Arrays

BLAST-TNG Production Arrays



250 μm Array
1836 Detectors

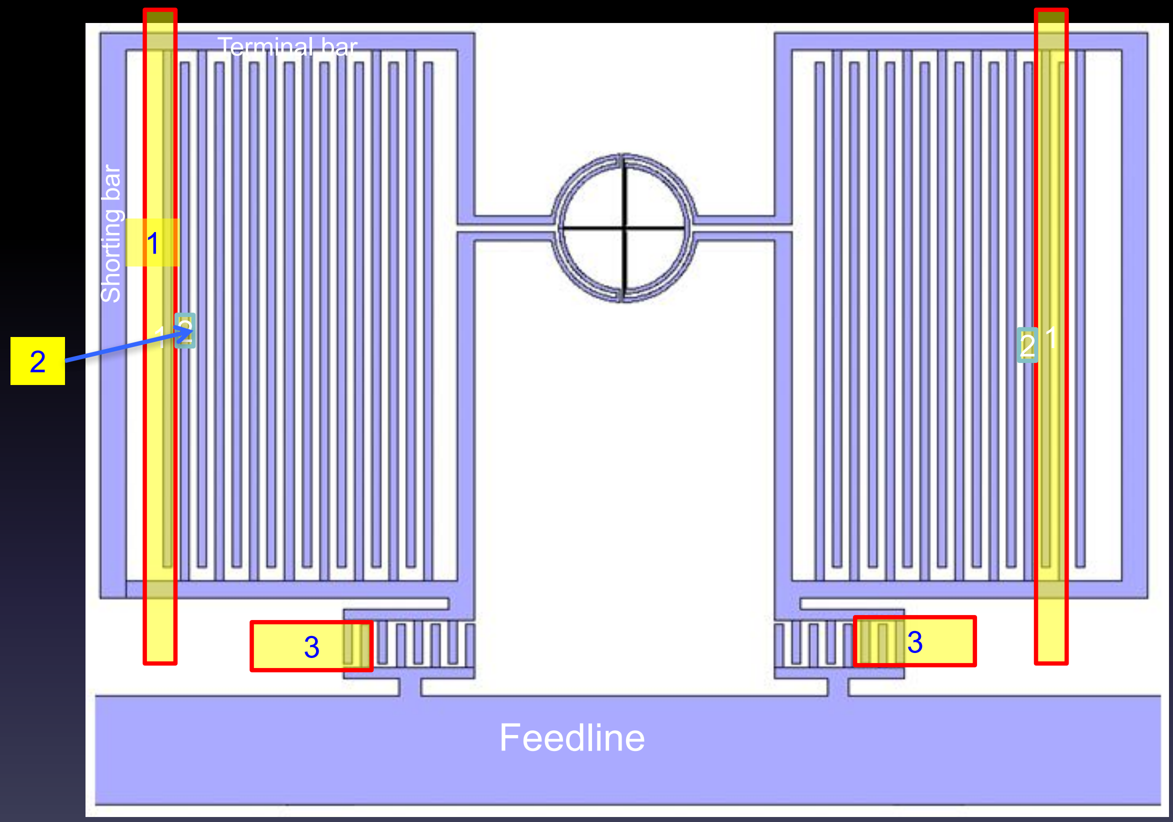
350 μm Array
938 Detectors

500 μm Array
544 Detectors

Frequency Definition & Distribution w/ Stepper

Stepper based solution:

1. Single standard pixel design imaged at every location
2. Series of “cuts” imaged to produce unique capacitors

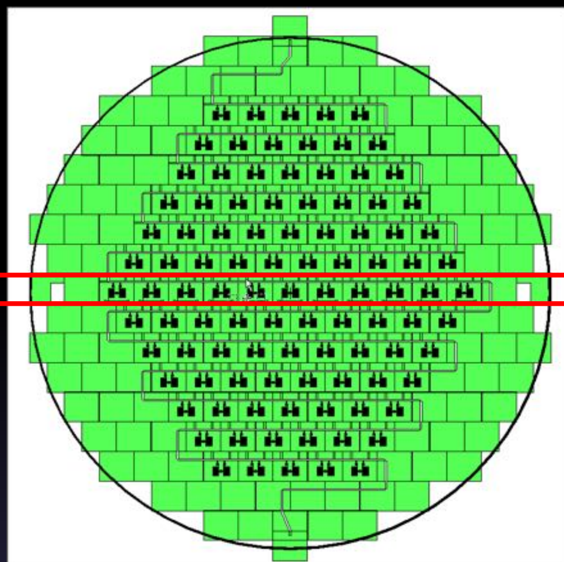


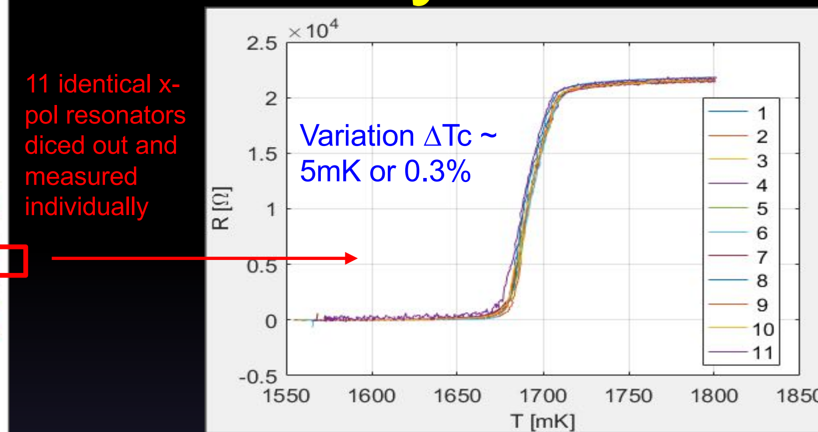
(1) IDC coarse cutter (X-cutter), (2) IDC fine cutter (Y-cutter), (3) Coupling IDC cutter

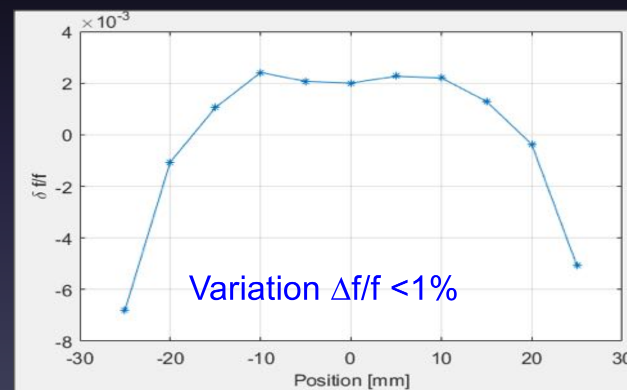
- Stepper job file defined the relative offset of the cutters to the template resonator.
- 7 flashes per pixel (or 5 flashes if X and Y cutters are combined).
- Resonator template mask are placed at the center of the reticle for best lithography quality.

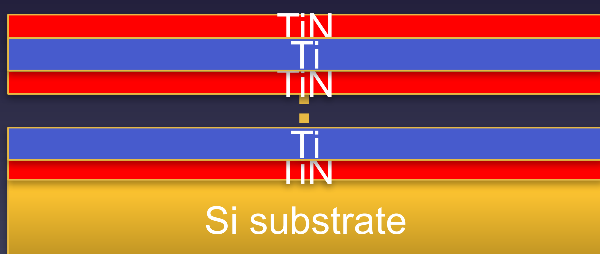
Array Uniformity

3-inch uniformity test wafer







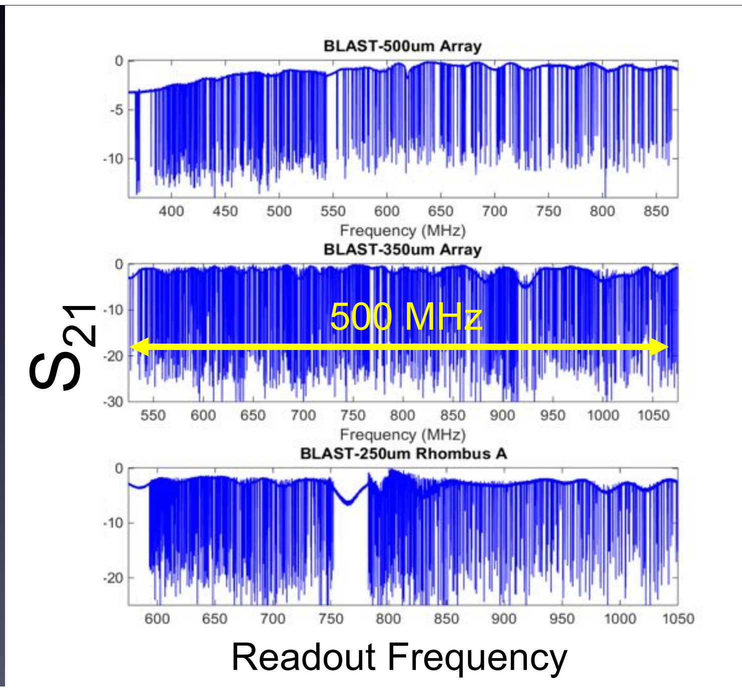


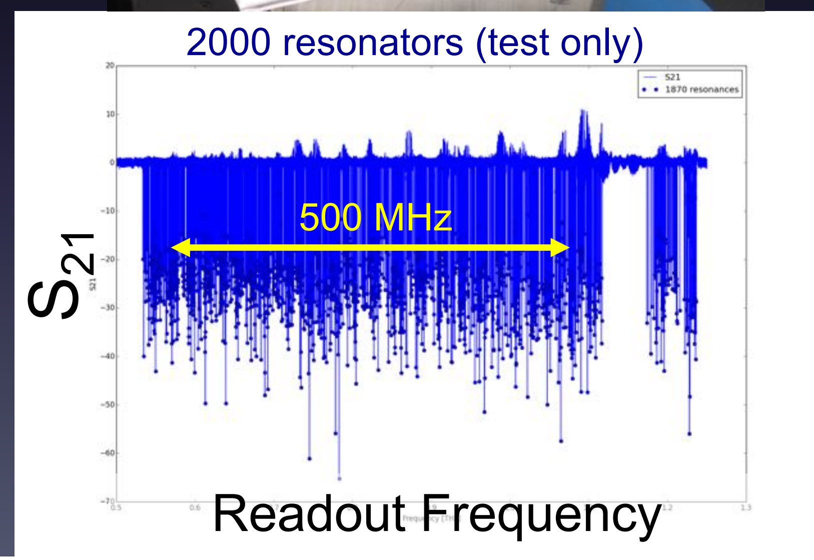
- TiN/Ti../TiN multilayer
- 7/10/7/10/7/10/7, total 60 nm
- R_{sn} ~ 20 Ω/sq, L_s ~ 20 pH/sq

With the measured radial dependence profile, correction can be applied to the design to further reduce the collision.

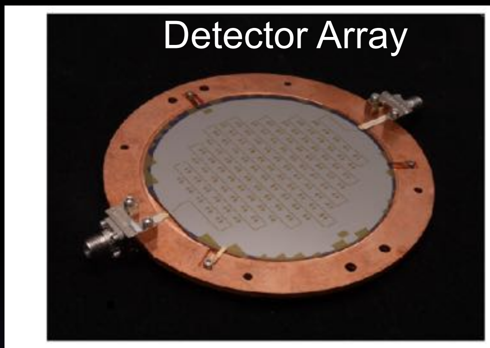
Arrays: densely populated networks

BLAST-TNG





Resonator-to-pixel mapping



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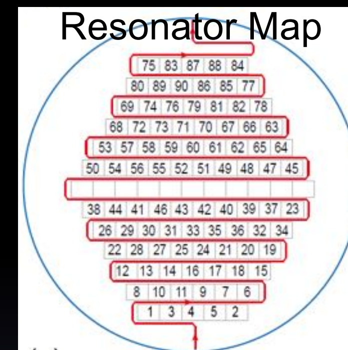
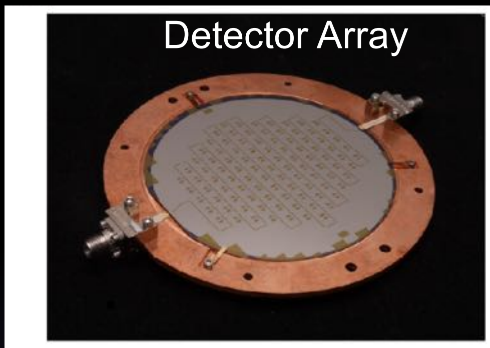
Physical map?

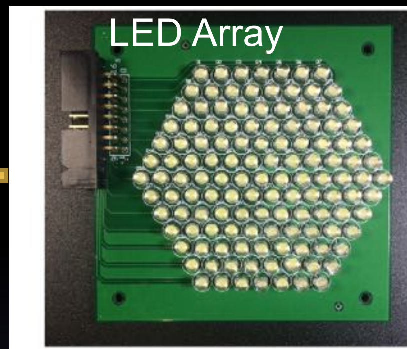


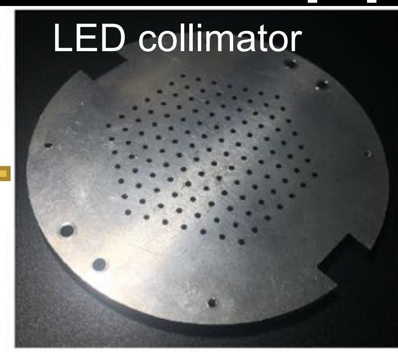
Problem 1

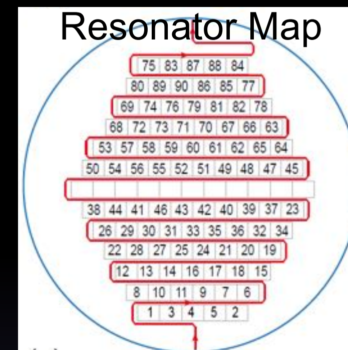
Errors in frequency placement can lead to an ambiguous mapping between physical detector and resonator

LED Trimmer/Mapper









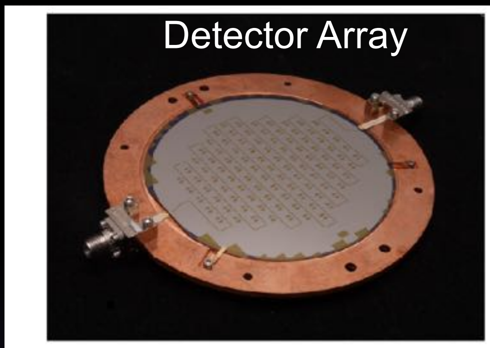
Use array of uniquely addressable cold LEDs to identify correspondence between resonator frequency and physical position

Problem 2
Frequency collisions can lead to a loss in usable yield

Y. Wang, *et al.* JAP (2017)

In collaboration with Y Wang, L.F Wei, *et al.* Southwest Jiaotong University, Chengdu, China

LED Trimmer/Mapper



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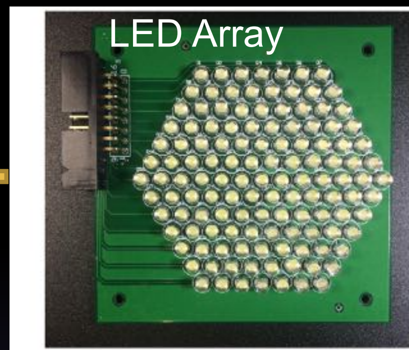

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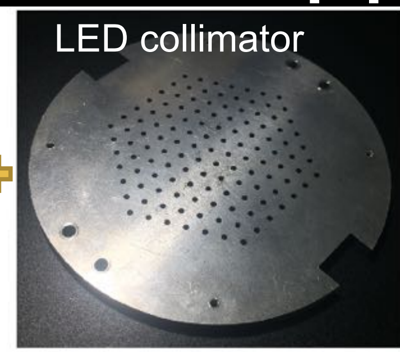

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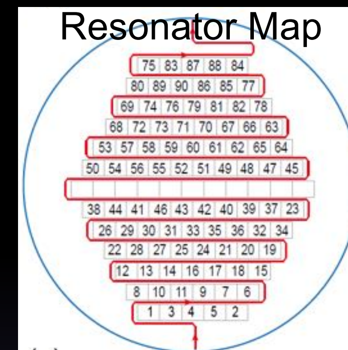
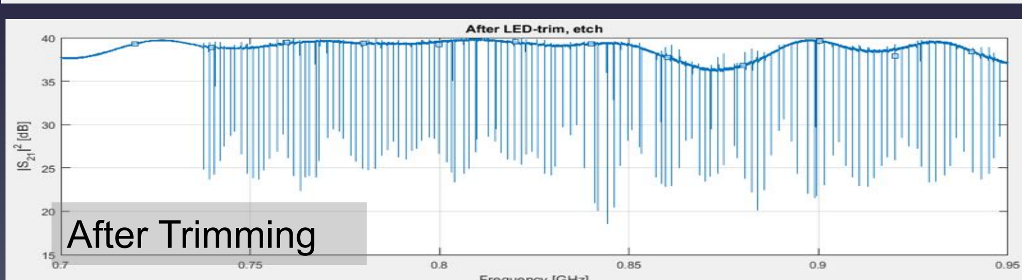
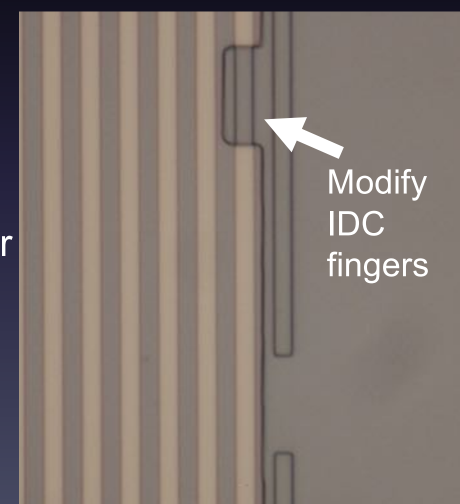


Use array of uniquely addressable cold LEDs to identify correspondence between resonator frequency and physical position



- Re-etch the resonators to correct for fabrication non-uniformity.
- Array of resonators after trimming etch much more uniform.
- Usable yield (5 LW) : 86% -> 98.5 %

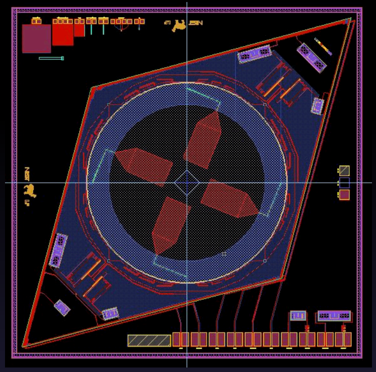


Y. Wang, *et al.* JAP (2017)

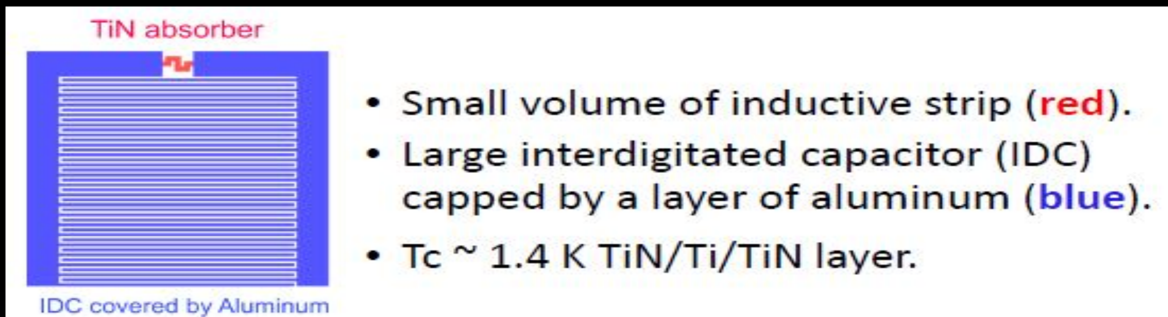
In collaboration with Y Wang, L.F Wei, *et al.* Southwest Jiaotong University, Chengdu, China

Other/Future Directions

- OMT based KID polarimeters
- Alternative materials & Hybrids
- Photon Counting

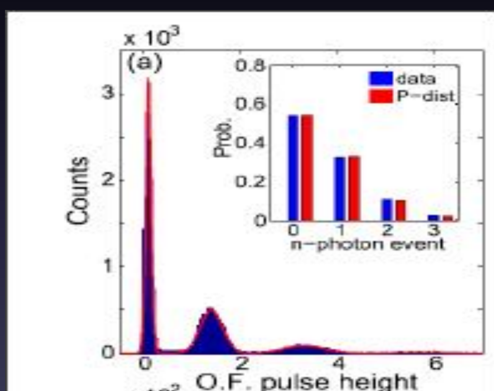


MKID photon counting detector at 1550nm

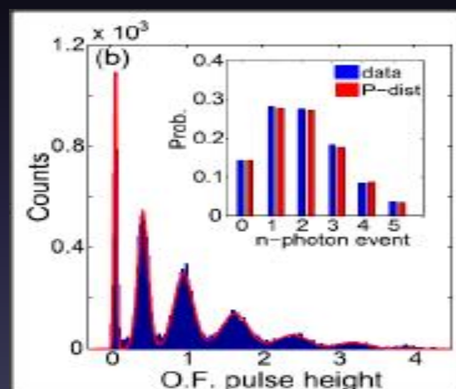


λ : mean # of photon per pulse

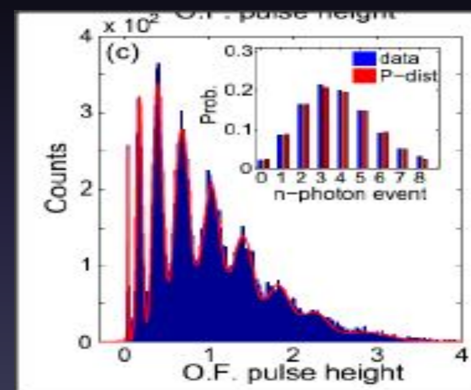
λ=0.61



λ=1.95



λ=3.78



W. Guo, etal. APL 110, 212601 (2017)

- Energy resolution of 0.22 eV at 1550nm.
- Resolving up to 7 photons per optical pulse.

In collaboration with Dr. Y. Wang at Southwest Jiaotong University, China

Summary

- Large monolithic KID-based Polarimeter arrays up to 150 mm diameter
- LED mapper + MLA modification could allow high multiplexing factors with nearly 100% yield
- Simplified fabrication for single-band focal planes allows for quick turnaround
- Excellent optical performance
  - Low cross-polarization
  - High optical efficiency over wide bandwidth
  - Photon-noise limited performance at experimental loads
- Ongoing: Optically induced 1/f noise remains most limiting factor for slowly modulated measurements
- Project quickly expanding to other designs, materials, coupling mechanisms, and photon energies