



A CRYOGENIC THZ CALIBRATION SYSTEM FOR ULTRA-SENSITIVE DETECTORS

Emily Perry (LBNL/UC Berkeley)

SLAC SQUAT/QPD Workshop 28-29th October 2025

Group involved:

Noah K., Betty Y., Emily S., Sidney S., Tonya P., Chiara S., Erin E., Brennan C.

MOTIVATION

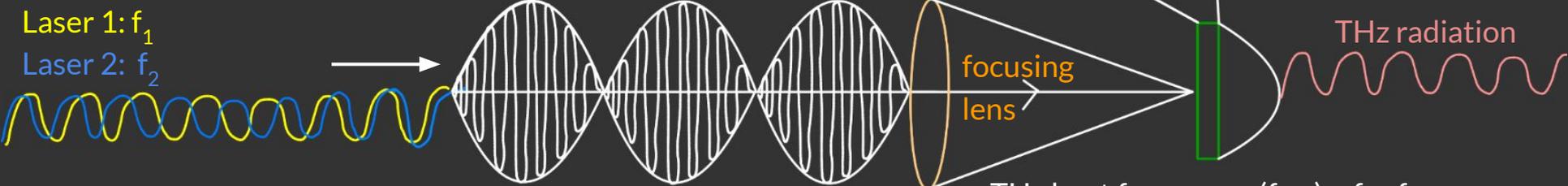
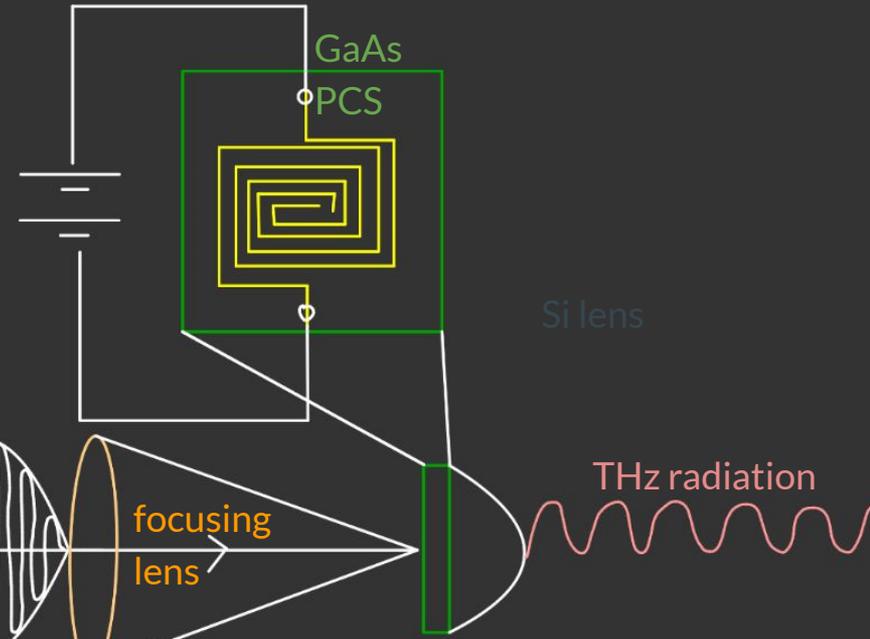
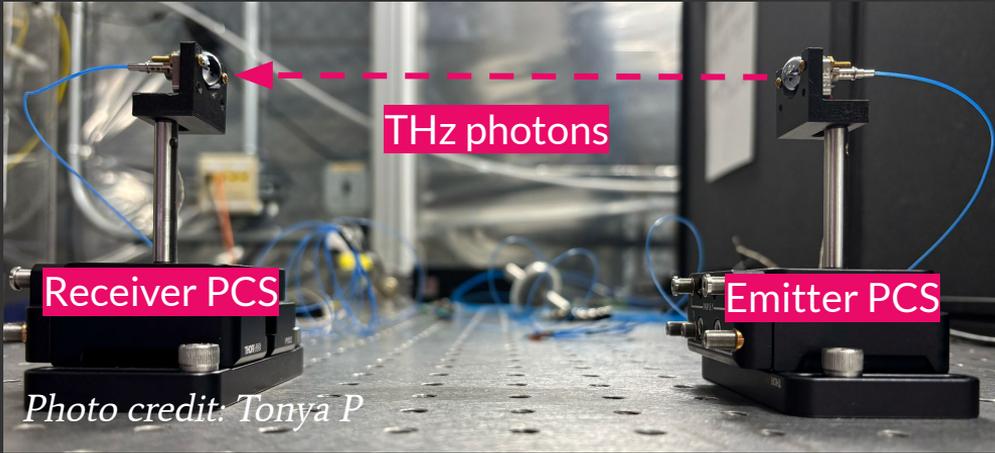
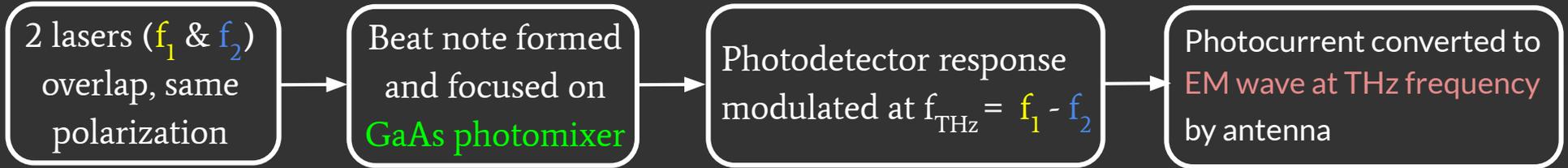
CHALLENGE : The calibration of ultra-sensitive THz/meV detectors in cryogenic environments is a significant challenge, as standard fiber optics absorb THz radiation and tunable sources are limited.

SOLUTION : A system is being developed using a photomixer and hollow circular waveguides to deliver tunable frequency THz photons to cryogenic sensors.

IMPACT : This work is motivated by the need to calibrate SQUATs, which are sensitive to single THz photons and meV phonons.

PRINCIPLE OF OPERATION

High frequency photomixing to generate and detect THz.

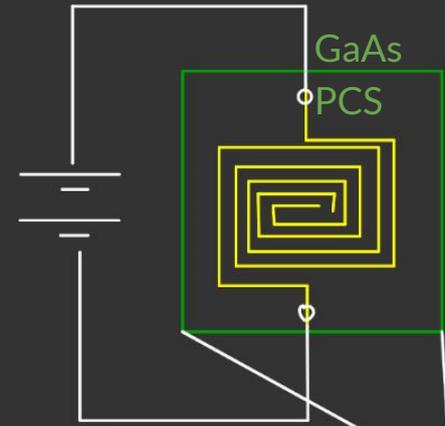
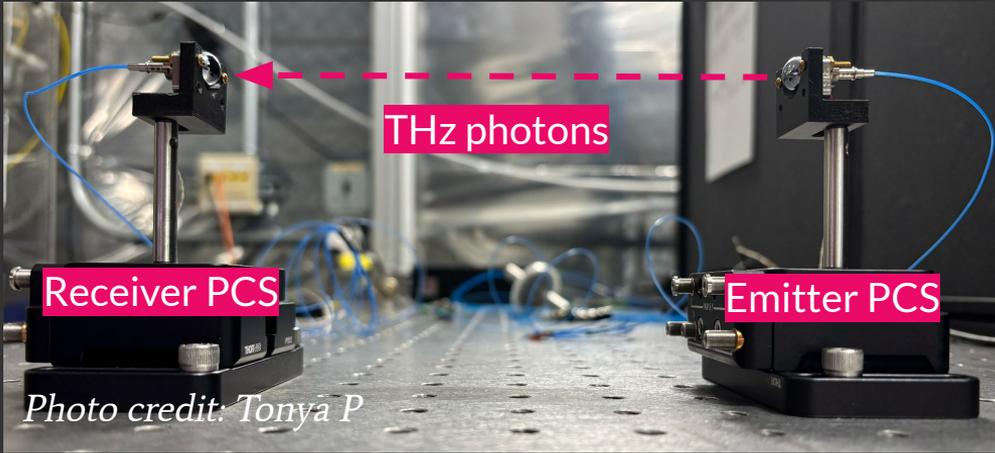
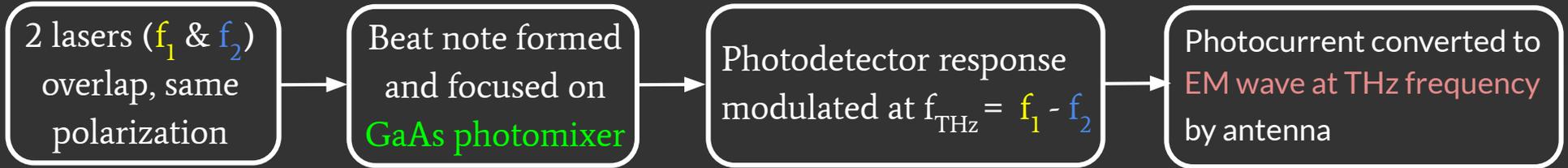


See backup slides for details

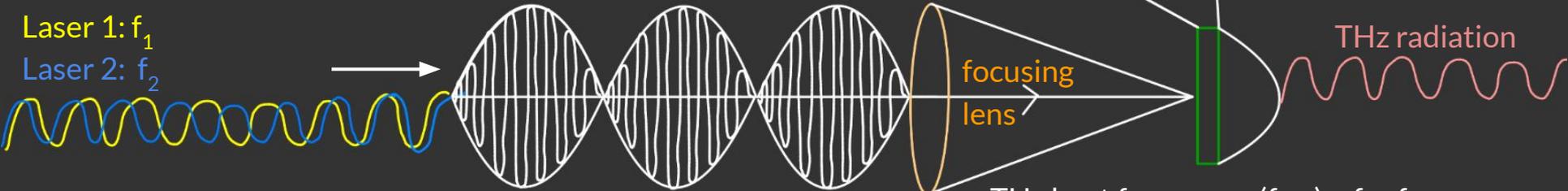
Emily Perry (eperry@lbl.gov)

PRINCIPLE OF OPERATION

High frequency photomixing to generate and detect THz.



Receiver: same but...
Larger optical path & e-h pairs accelerated by THz radiation.
Lock in amplifier used to measure current



See backup slides for details

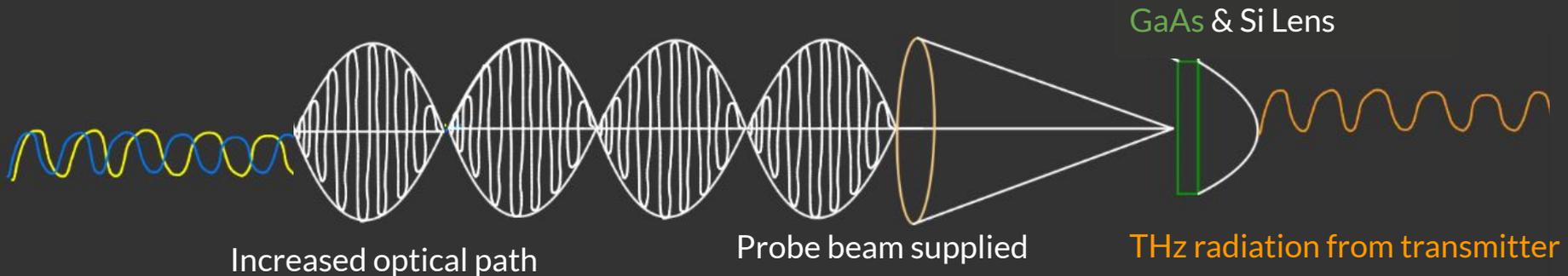
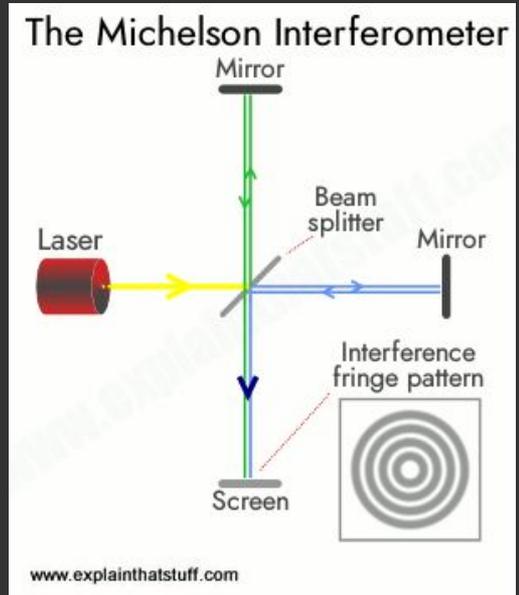
Emily Perry (eperry@lbl.gov)

HOW DO WE DETECT THZ?

Same combined laser beam sent down a longer optical path to detector PCS onto which the THz signal is incident

Basically an interferometer!

1. Light Source : laser
2. Beam Splitter : 2 beams, a probe beam and a test beam.
3. Optical Paths: probe beam travels a longer fixed path. Test beam travels along a changeable path (by distance)
4. Interference Pattern



1. Several S/N Improvements:

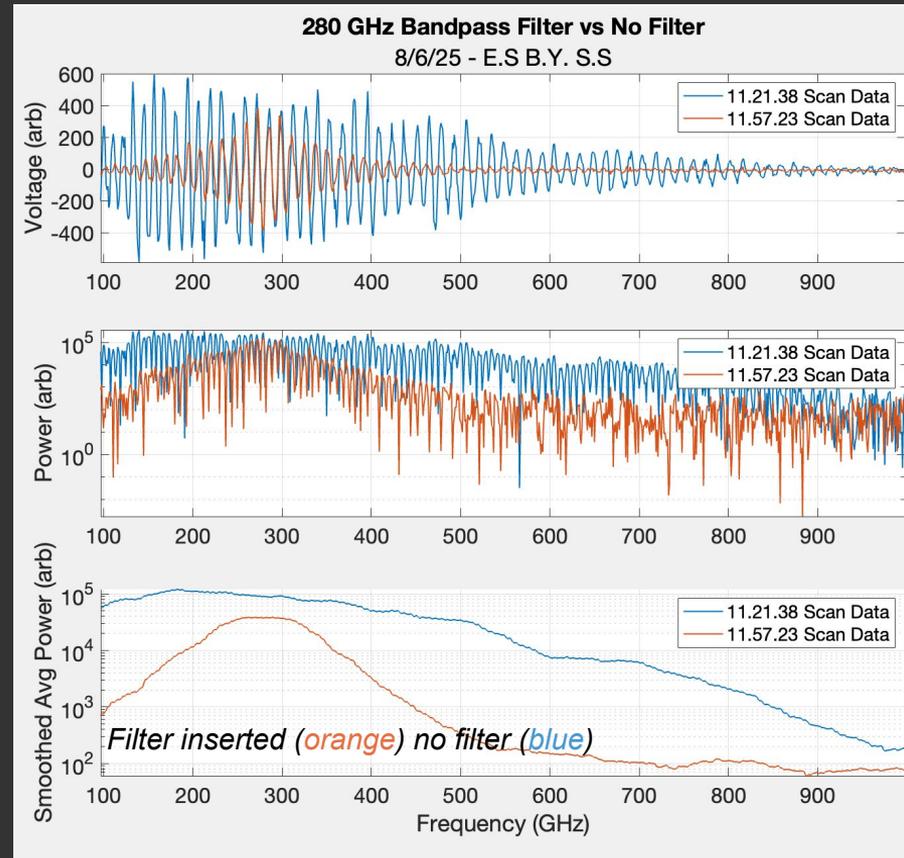
- Cables modifications: shielding, twisted pair
- New grounding schemes: remove voltage offset
- Faraday cage alterations: two orders of magnitude higher signal.
- As a result the "EMI noise" previously observed has been significantly reduced, though a lower-level intrinsic noise source remains.

2. Winston Cone tests

3. Waveguides: needed for longer-term

4. Sourcing of new photo-mixer heads for better alignment

5. Collaborating on THz → SQUAT design

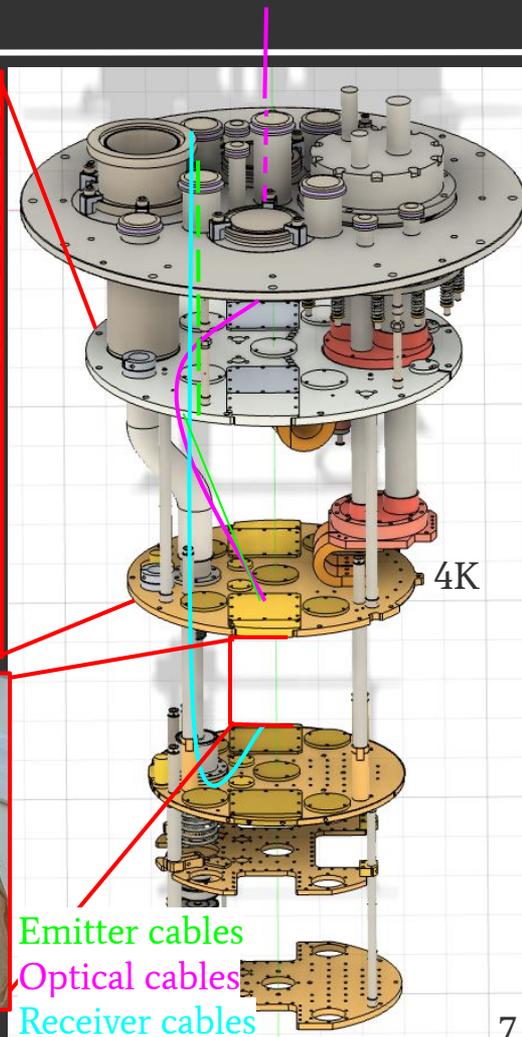
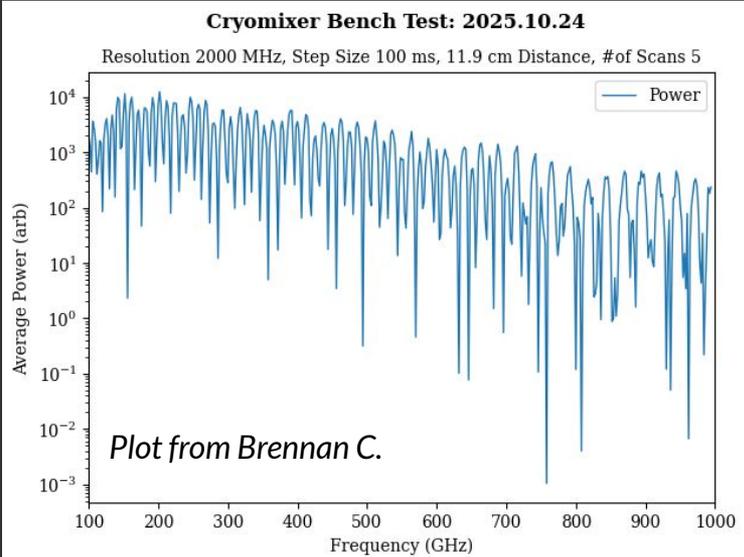


From Betty & Emily S. With a 12.6 ± 0.2 cm PSD head spacing.

4K INTERIM FRIDGE OPERATION @ BERKELEY

Goal: THz being sent to SQUATs at the LD400 MXC.
Interim test: photomixer head setup at 4K stage.

Currently working on moving THz system into the LD400 after bench top testing for familiarisation



FUTURE WORK



4K INTERIM TESTING:

- Installation of THz system in LD400 and initial room & cold temperature testing/alignment

1K INTERIM TESTING: *Ideally new PSD heads*

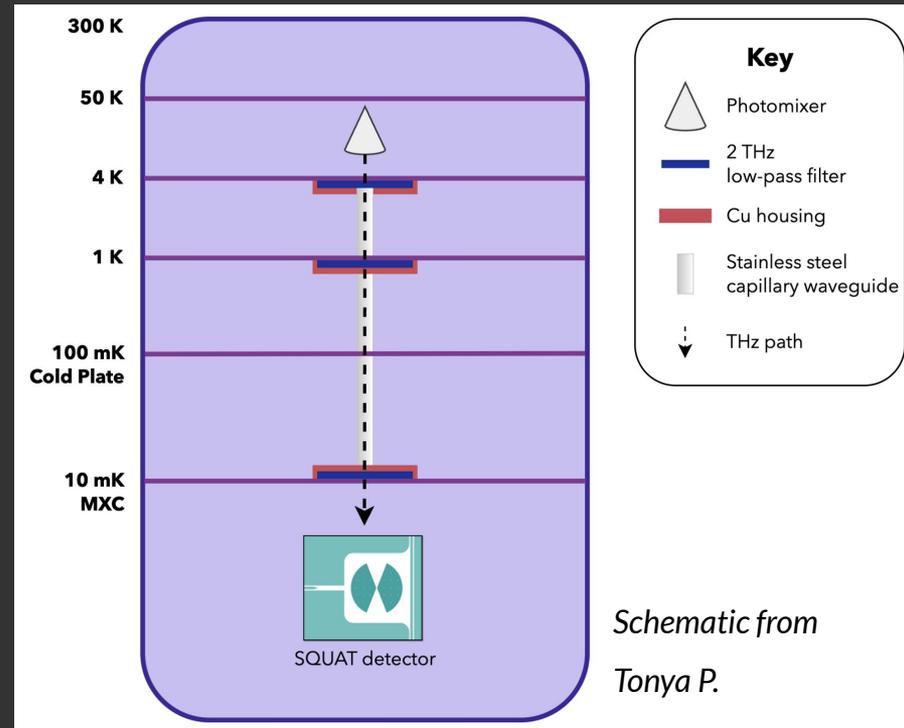
- Modification of existing 4K set up (waveguide etc.)
- Room & cold temperature testing/alignment

FUTURE WORK

THZ → SQUAT CALIBRATION:

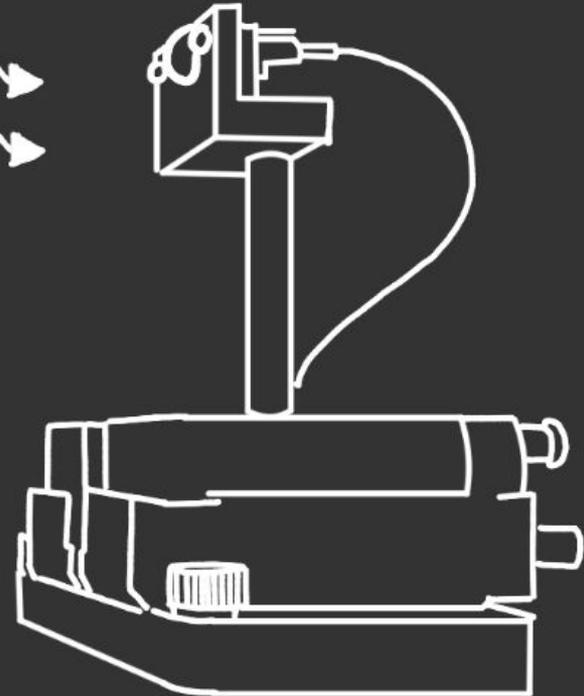
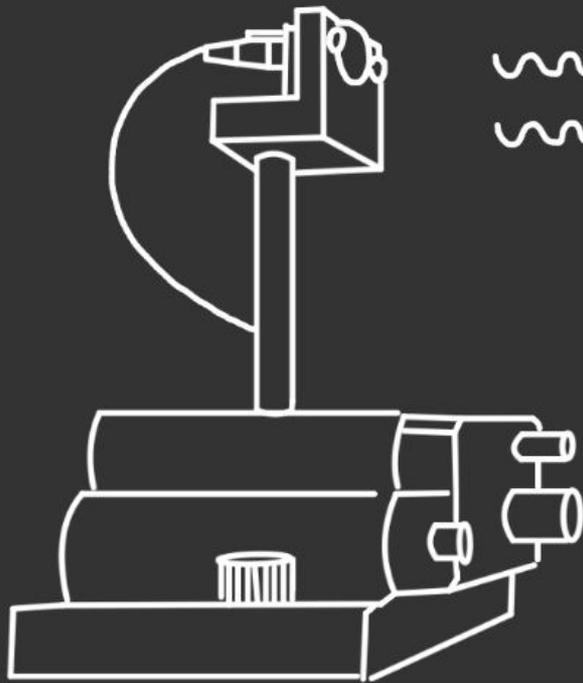
Design work being done in collaboration with SLAC

- Design considerations:
 - Thermal shorting considerations
 - Waveguide or free-space coupling
 - Blackbody radiation filtering
 - Beam considerations diffraction, etc
 - Robustness necessary for transfer to other systems (e.g BREAD)

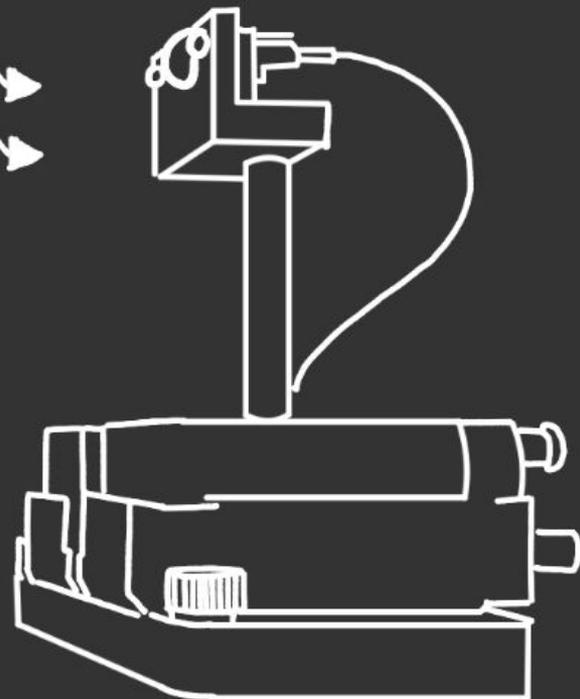
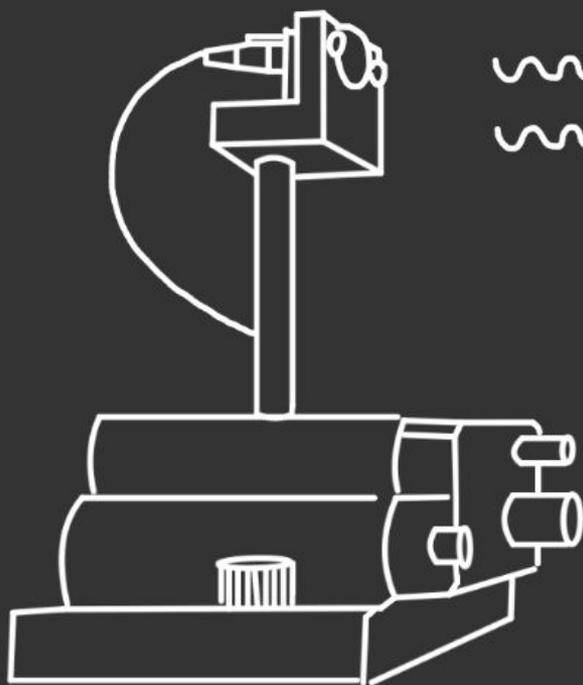


Future future : combining system with MEMs! See Sidney's talk

THANK YOU!



BACKUP



OTHER CALIBRATION METHODS

- JJ injectors
- Filtered black bodies
- Radioactive sources
- Frequency multipliers

Effect of current injection into thin-film Josephson junctions

[V. G. Kogan](#)^{1,*} and [R. G. Mints](#)^{2,†}

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Phys. Rev. B **90**, 184504 – Published 11 November, 2014

DOI: <https://doi.org/10.1103/PhysRevB.90.184504>

JJ controlled by a current circulated through two or more attached microinjectors. This allows for manipulation of the junction's energy profile.

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Inherent Thermal-Noise Problem in Addressing Qubits

[Slawomir Simbierowicz](#) [†], [Massimo Borrelli](#) , [Volodymyr Monarkha](#) , [Ville Nuutinen](#), and [Russell E. Lake](#) ^{*}

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They can incorporate filters that precisely shape the spectral output of the blackbody to mimic or isolate specific types of noise, as seen in this AIP article.

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PRX Quantum **5**, 030302 – Published 2 July, 2024

DOI: <https://doi.org/10.1103/PRXQuantum.5.030302>

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Efficient Qubit Calibration by Binary-Search Hamiltonian Tracking

[Fabrizio Berritta](#) ^{1,2}, [Jacob Benestad](#) ³, [Lukas Pahl](#) ^{1,4}, [Melvin Mathews](#) ^{1,5}, [Jan A. Krzywda](#)⁶, [Réouven Assouly](#) ¹, [Youngkyu Sung](#) ^{1,4}, [David K. Kim](#)⁷, [Bethany M. Niedzielski](#) ⁷ *et al.*

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PRX Quantum **6**, 030335 – Published 26 August 2024

DOI: <https://doi.org/10.1103/77qg-p68k>

Involve calibrating microwave components to generate higher, precise frequencies for qubit control

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RESEARCH ARTICLE | NOVEMBER 15 2023

Robust cryogenic matched low-pass coaxial filters for quantum computing applications

[Anton I. Ivanov](#) , [Victor I. Polozov](#) , [Vladimir V. Echeistov](#) , [Andrey A. Samoylov](#) , [Elizaveta I. Malevannaya](#) , [Alekssei R. Matanin](#) , [Nikita S. Smirnov](#) , [Ilya A. Rodionov](#)  

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Appl. Phys. Lett. **123**, 204001 (2023)

<https://doi.org/10.1063/5.0177092> Article history 

OTHER CALIBRATION METHODS

Method	Description	Pros	Cons
THz calibration system	Supply THz via photomixing directly to SQUATs at cryogenic temperatures	Directly supplying signal you want to measure. Broadband, robust Cryogenically compatible (starts in fridge)	R&D needed for design, expensive
Josephson junction injectors	JJ controlled by a current circulated through two or more attached microinjectors. This allows for manipulation of the junction's energy profile.	High sensitivity, exact manipulation Cryogenically compatible (starts in fridge)	Modelling complications/extensive amount required because of spread of JJ prop (critical current). Not tunable
Filtered black bodies	They can incorporate filters that precisely shape the spectral output of the blackbody to mimic or isolate specific types of noise, as seen in this AIP article.	Reproduction of noise profile Cryogenically compatible (starts in fridge)	Slower on/off. Not tunable
Frequency multipliers	Involve calibrating microwave components to generate higher, precise frequencies for qubit control	Minimal hardware, cost reduction. Also supplying signal here	frequency multiplication is that the phase noise of the input signal is also multiplied by the same factor 13

PRINCIPLES OF OPERATION

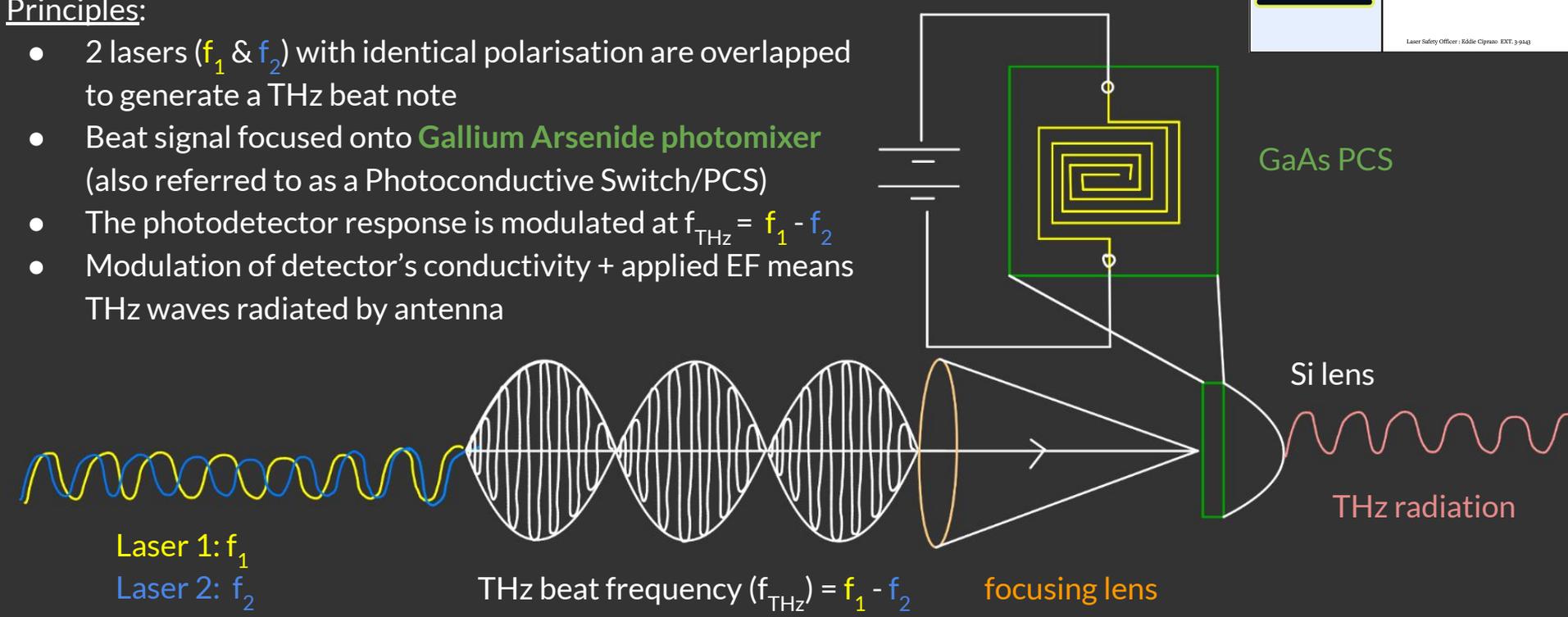
WARNING	
	CLASS 3B LASER CONTROLLED AREA LASER RADIATION AVOID DIRECT EYE EXPOSURE TO BEAM LASER EYE PROTECTION REQUIRED Laser Type/Max Power: <small>Laser Safety Officer: Eddie Cipriano EXT: 3-943</small>

High frequency photomixing to generate and detect THz radiation.

CLASS 3B LASER CONTROLLED AREA

Principles:

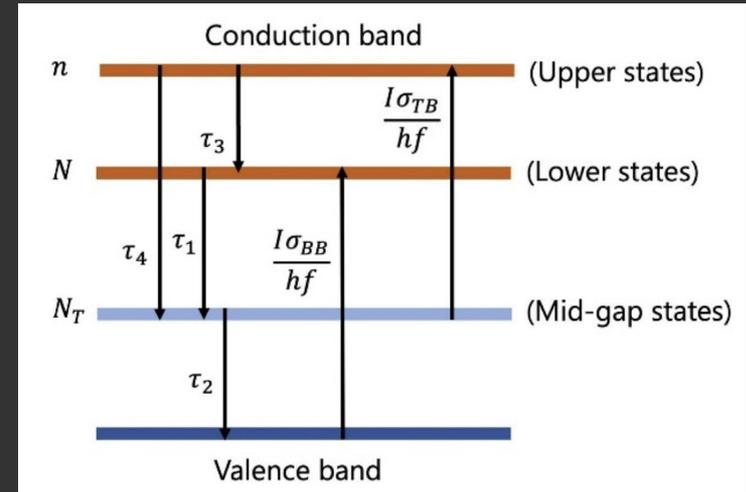
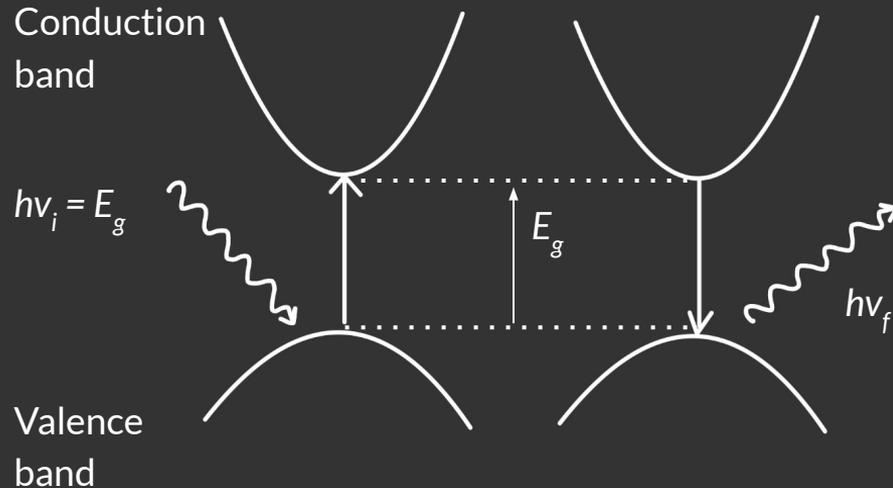
- 2 lasers (f_1 & f_2) with identical polarisation are overlapped to generate a THz beat note
- Beat signal focused onto **Gallium Arsenide photomixer** (also referred to as a Photoconductive Switch/PCS)
- The photodetector response is modulated at $f_{\text{THz}} = f_1 - f_2$
- Modulation of detector's conductivity + applied EF means THz waves radiated by antenna



HOW PCS's WORK

Photoconductive switching:

- The photons from the combined laser beams are absorbed by the LTG-GaAs semiconductor, generating electron-hole pairs
- LTG-GaAs a very short carrier lifetime
→ generation and recombination of charge carriers is quick
→ enables electrical conductivity to oscillate with the beat freq.



L N F Dela Rosa et al 2024 *Semicond. Sci. Technol.*
39 075010

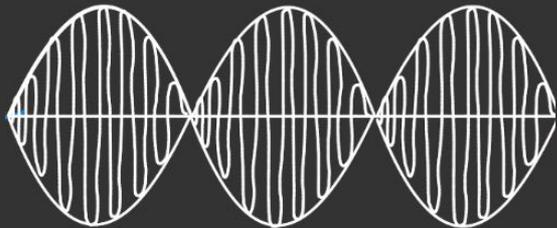
HOW PCS's WORK

Photoconductive switching:

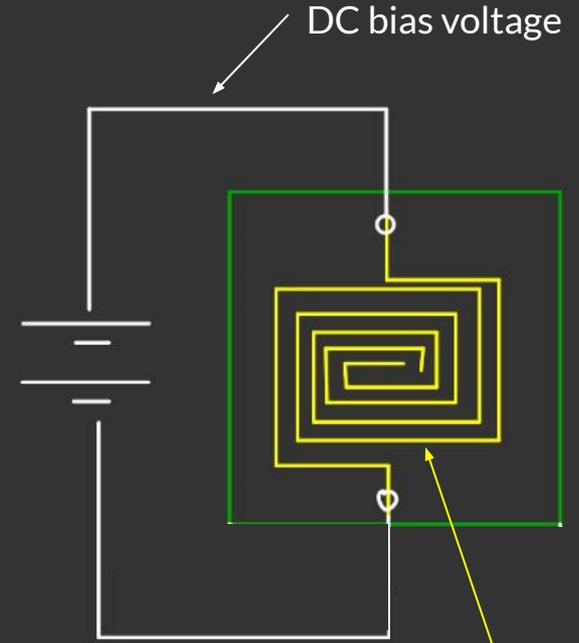
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Photocurrent generation:

- DC bias voltage applied to the interdigitated **electrodes*** drives charge carriers, creating a photocurrent.
- Because the # carriers is modulated at the beat freq (f_{THz}), the photocurrent also oscillates at f_{THz}



$$\text{THz beat frequency } (f_{\text{THz}}) = f_1 - f_2$$



*interdigitated electrodes are **electrodes** with a “finger locked” pattern. Provides a high surface area in a small volume, ideal for sensing applications.

HOW PCS's WORK

Photoconductive switching:

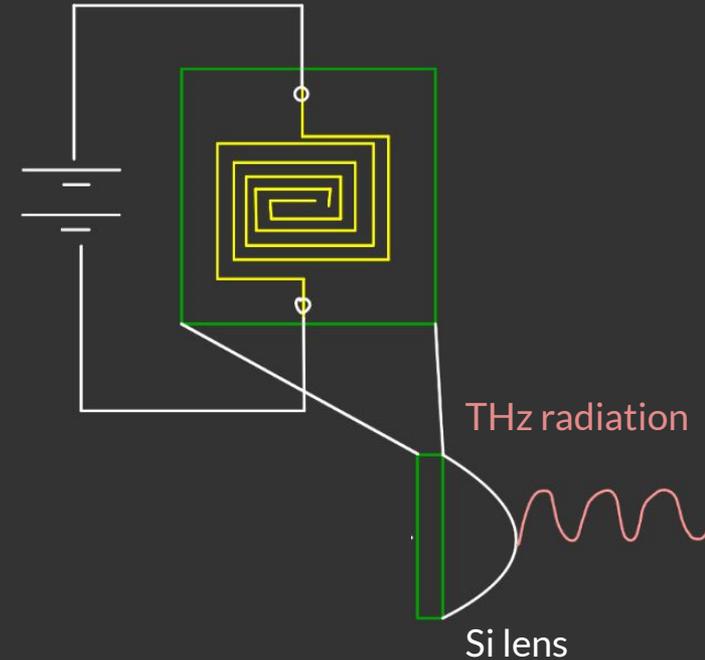
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Photocurrent generation:

- DC bias voltage applied to the interdigitated electrodes* drives charge carriers, creating a photocurrent.
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THz radiation:

- Photocurrent travels to the integrated antenna, which converts the electrical current into a corresponding **electromagnetic wave at the terahertz frequency.**
- The antenna radiates this signal into free space, and a silicon lens is attached to the back of the device to improve signal coupling.



HOW DO WE DETECT THZ?

- The THz system uses a **coherent detection technique**

	Coherent	Incoherent
Signal inputs	Amplitude (A) & phase (ϕ) - measures the entire complex amplitude	Intensity (I) & power (P)
Operating principle	Involves a receiver that uses a local oscillator (a laser) that is synchronized with the phase and frequency of the original transmitted signal & mixes the 2.	The receiver does not need to synchronize with the transmitted signal phase. It detects the signal based on its magnitude or power. Does not detect phase changes
Advantages	Noise cancelling , greater sensitivity, retains phase information	Simplicity, bulk deployment (low cost), more robust
Applications	Air traffic control radar and long-haul fiber-optic communication	Navitagation, radar detection

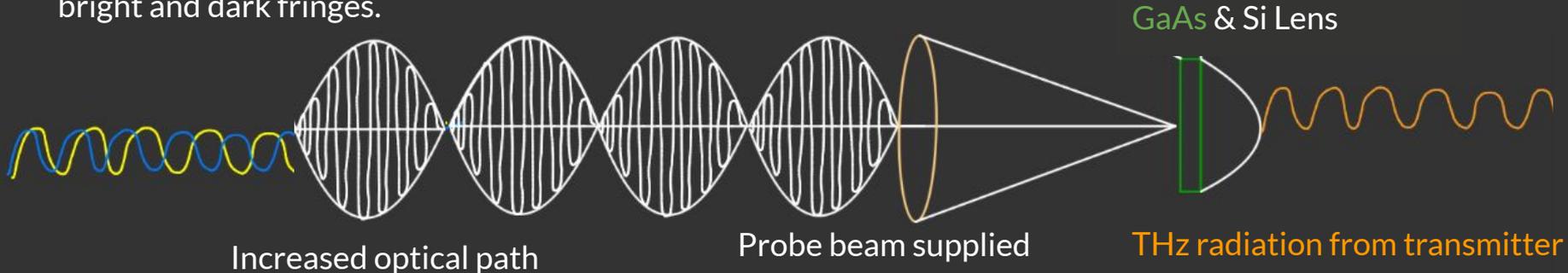
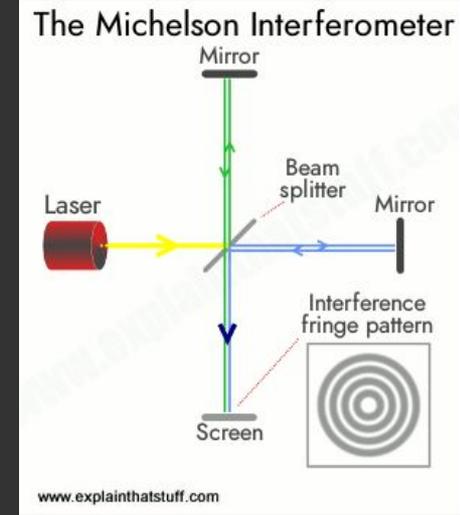
HOW DO WE DETECT THZ?

How is coherent detection achieved with the THz system?

- **homodyne detection:** same combined laser beam sent down a longer optical path to detector PCS onto which the THz signal is incident

Basically an interferometer!

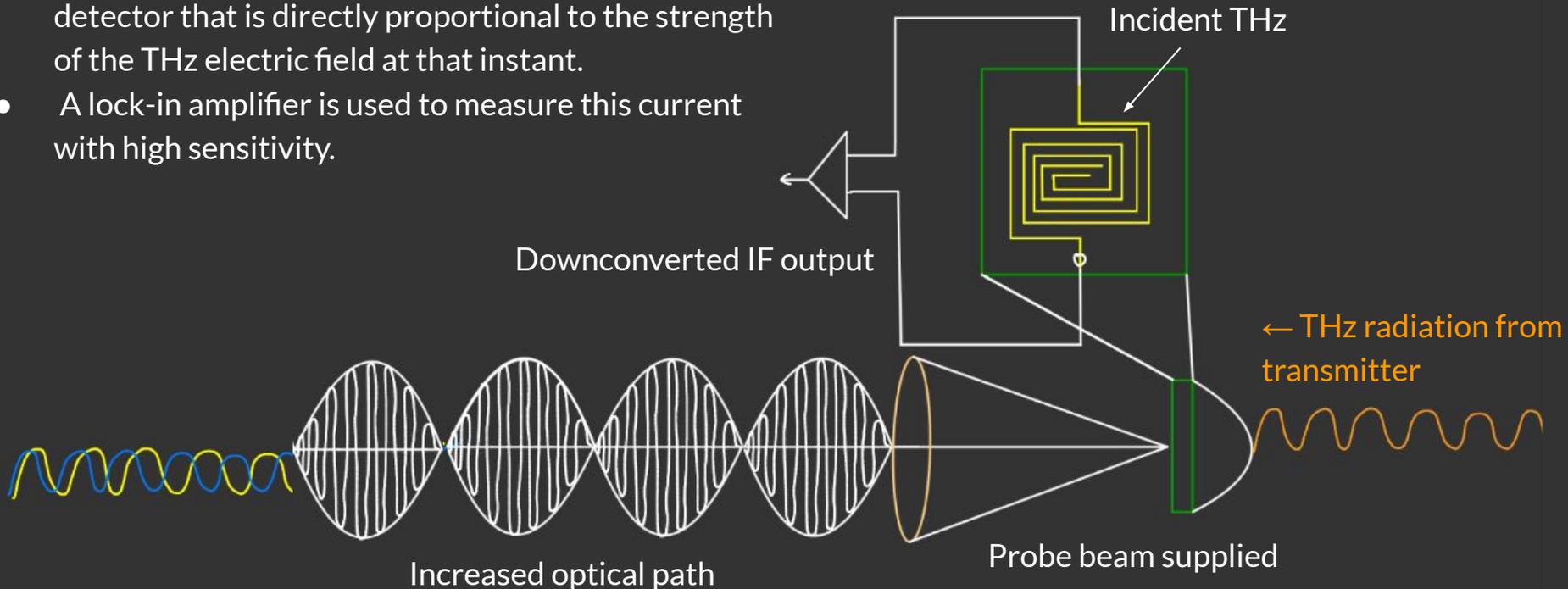
- **Light Source:** A light source, often a stable laser, provides the light.
- **Beam Splitter:** division of light into 2 beams: a probe beam and a test beam.
- **Optical Paths:** The probe beam travels a longer fixed path. The test beam travels along a path that is changed (by distance)
- **Interference Pattern:** Waves recombined producing interference pattern of bright and dark fringes.



HOW DO WE DETECT THZ?

Similar to before...

- Probe beam causes electron-hole pairs to be generated as before
- But this time these charge carrier are accelerated by the incident THz radiation
- This acceleration produces a small current in the detector that is directly proportional to the strength of the THz electric field at that instant.
- A lock-in amplifier is used to measure this current with high sensitivity.



A Cryogenic THz Calibration System for Ultra-Sensitive Sensors: Design and Initial Tests

Tonya L. Peshel^{1,2}

Sidney A. Stevens^{1,2}, Chiara P. Salemi^{3,4}, Noah Kurinsky^{1,2}, Kelly Stifter^{1,2}, Holden I. Kowitz^{3,4}, Emily Perry^{3,4}

¹Kavli Institute for Particle Astrophysics and Cosmology, ²Stanford University; ³SLAC National Accelerator Laboratory; ⁴University of California, Berkeley; ⁵Lawrence Berkeley Laboratory

Motivation

Delivering broadband THz photons into a cryogenic environment is a critical calibration challenge for THz/meV detectors, as fiber optics absorb THz radiation and tunable sources are limited. We are developing a system to calibrate cryogenic THz/meV detectors using hollow circular waveguides.

Our labs work on Superconducting Quasiparticle-Amplifying Transistors (SQUATs), which are sensitive to single THz photons and meV photons by detecting tunneling events through readout of the qubit transition frequency (Fig. 1)

The successful integration of THz photons with superconducting qubits would significantly enhance the sensitivity of dark matter searches, and could be used directly in experiments such as the Broadband Reflector Experiment for Axion Detection (BREAD), which will search for low-mass axions. (Fig. 2)

Here, we report progress toward a full-system setup to validate photomixer performance and test waveguide transmission in a 4K cryostat.

SQUAT Design

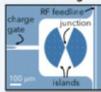


Figure 1 [1]

BREAD Schematic

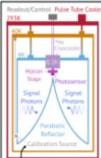


Figure 2 [2]

THz Photomixers

Bakman Technologies PB7300 Spectrometer

- Tunable, high-resolution, broadband (0.1 – 1.9 THz)
- Can be used to deliver THz photons to our SQUAT detectors
- Warm system used for Cu waveguide & filter characterization
- Cold system being prep'd for cryogenic operation (Fig. 3)

	Warm Photomixers	Cold Photomixers
Operation Temperature	293 K	4 K
Si Lens Diameter	12.8 mm	10 mm
Si Lens Thickness	7.75 mm	7.3 mm
Si Lens Shape	Hyper-hemisphere	Hyper-hemisphere
Photomixer Thickness	0.5 mm	0.5 mm
Photomixer Spot Size	20 μm	20 μm
Beam Profile	Divergent 15° full	Collimated 6 mm FWHM

Preparing for Cryogenic Operation

Short Term Goal: Cryomixer Performance Validation

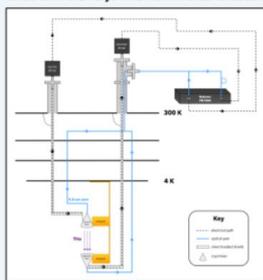


Figure 3: Experimental setup for testing photomixer performance in a 4K cryostat

Long Term Goal: SQUAT Calibration

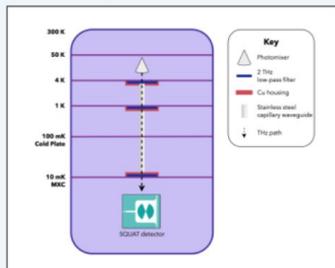
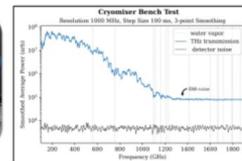


Figure 4: Calibrating SQUAT detectors in a dilution refrigerator

Results: Bench Testing Transmission



Objective

- Validate room temperature performance of cryogenic photomixers

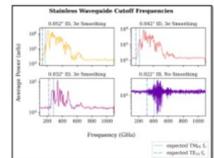
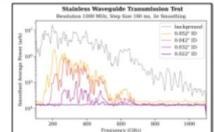
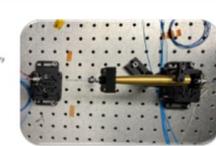
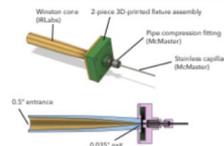
Results

- Higher frequency signal (>1.2 THz) drops below electromagnetic interference (EMI) noise floor

Design Requirements

- Better shielding of electronic components to prevent pickup

Results: Stainless Steel Capillary Waveguides



Winston Cone

- Concentrates incoming THz radiation to 0.035" exit diameter (non-imaging)
- High angular acceptance, though tip/fit alignment is necessary

Results & Conclusions

- Successful transmission through waveguides
- Cutoff frequencies match expected values
- Drop in attenuation with ID likely due to misalignment

Design Requirements

- Optimal transmission across all frequencies will require some tip/fit adjustment
- Full transmission not needed for calibrating low-threshold single photon detectors

Future Work

Finalize Cryomixer Mount Design

- Incorporate tip/fit and translation
- Protect fragile Si lens without blocking beam

Continue Waveguide Characterization

- Break tests, loop radius tests

Improve Electromagnetic Interference Shielding

- Increase SNR at higher frequencies



v2 Cryomixer Mount

Grand Vision

- Use as reliable source for superconducting detectors (SQUATs and beyond)
- Explore other applications, e.g. Probe far-Infrared Mission for Astrophysics (PRIMA) telescope (1.3 – 12.5 THz) [Mouillet 2023]

References

1. Superconducting quasiparticle-amplifying transistor: A qubit-based sensor for meV-scale photons and single terahertz photons, Phys. Rev. Applied 22, 054009 (2024)
2. Broadband Solenoidal Helioscope for Terahertz Axion Detection, Phys. Rev. Letters 128, 131801 (2022)

Acknowledgments

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