Miniaturized Microwave Absolute Calibration (MiniMAC) for Atmospheric Remote Sensing from Small Satellites

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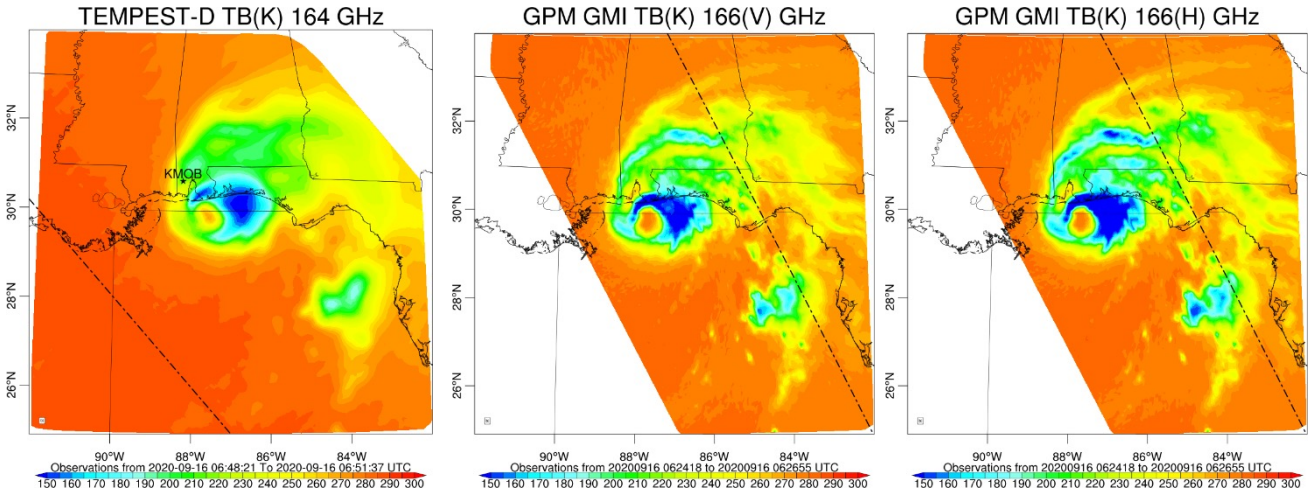
Motivation for MiniMAC

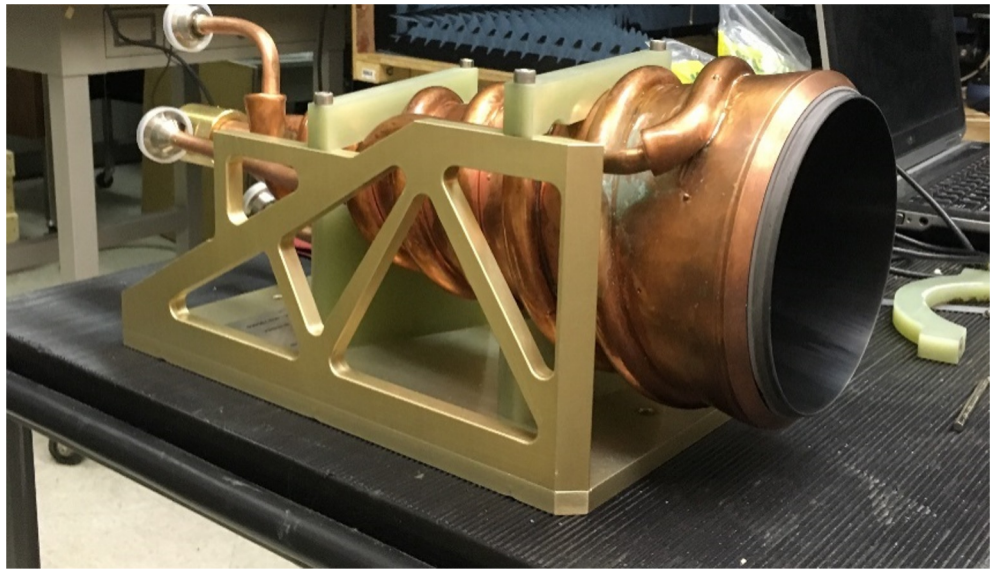
- CubeSat missions such as TEMPEST-D, RainCube and the TROPICS Pathfinder / Constellation have clearly demonstrated well-calibrated and validated passive and active microwave observations of atmospheric processes on a global basis.
- Capabilities of these CubeSat sensors have been demonstrated to be equivalent to those of operational sensors (*Berg et al., IEEE TGRS, 2021*).



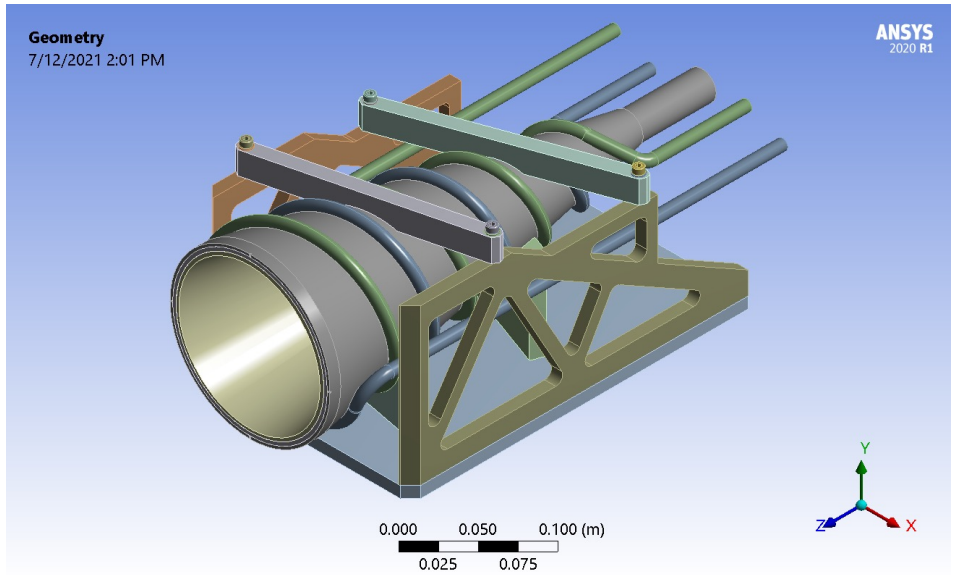
TEMPEST-D and GMI Observations of Hurricane Sally on Sept. 19, 2020

- "NewSpace" developments of CubeSats and SmallSats provide a rapidly increasing myriad of opportunities for deployment of on-orbit microwave sensors and satellite constellations.
- An improved method is needed to determine the calibration accuracy and precision of new sensors to further improve the fidelity of future global weather and climate observations.

NIST Brightness Temperature Calibration Target for SI Traceability



NIST Blackbody Calibration Target



Thermal Model of NIST Blackbody Target

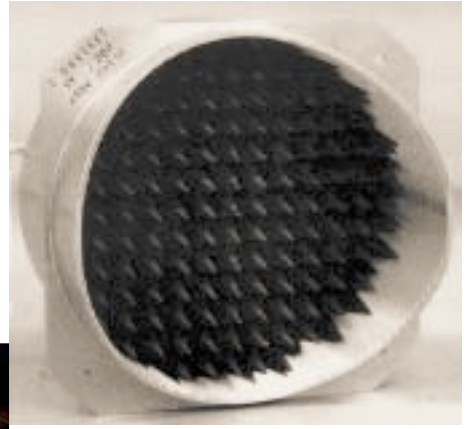
Key Benefits

- SI traceability of pre-launch instrument calibration
- Improves accuracy of microwave sensors during on-ground validation
- Reduces time and effort needed for on-orbit calibration and validation
- Improved characterization of heterogeneous passive microwave sensors

Miniaturized Calibration Targets

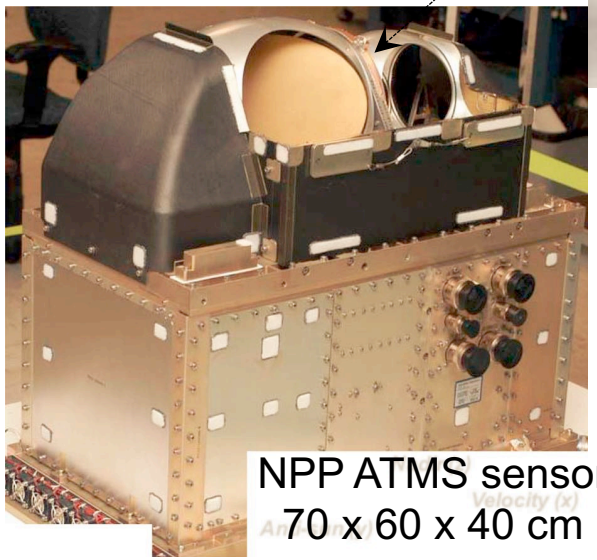
Develop, Produce and Validate Innovative Metamaterial Calibration Targets

State of the Art



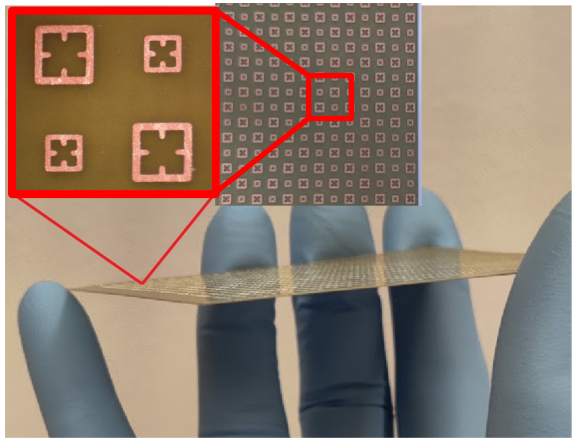
ATMS Blackbody Calibration Target

(inside)



NPP ATMS sensor
70 x 60 x 40 cm

Game-Changing Technology



Planar Metamaterial Target for On-orbit Calibration on Small Satellites

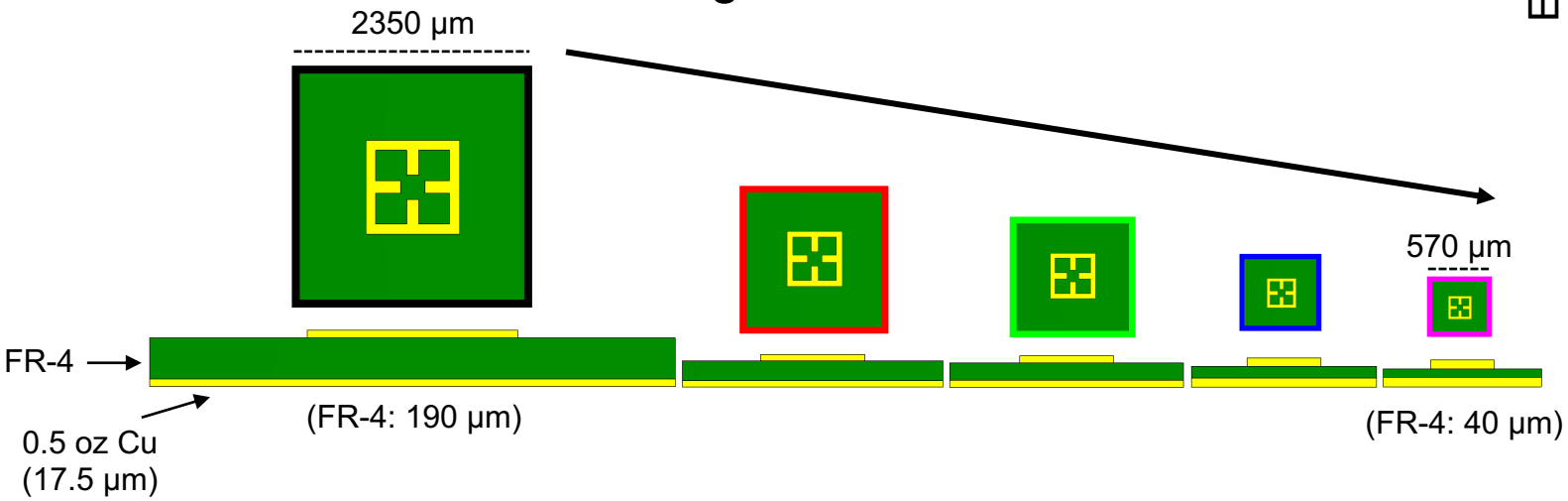
Key Benefits:

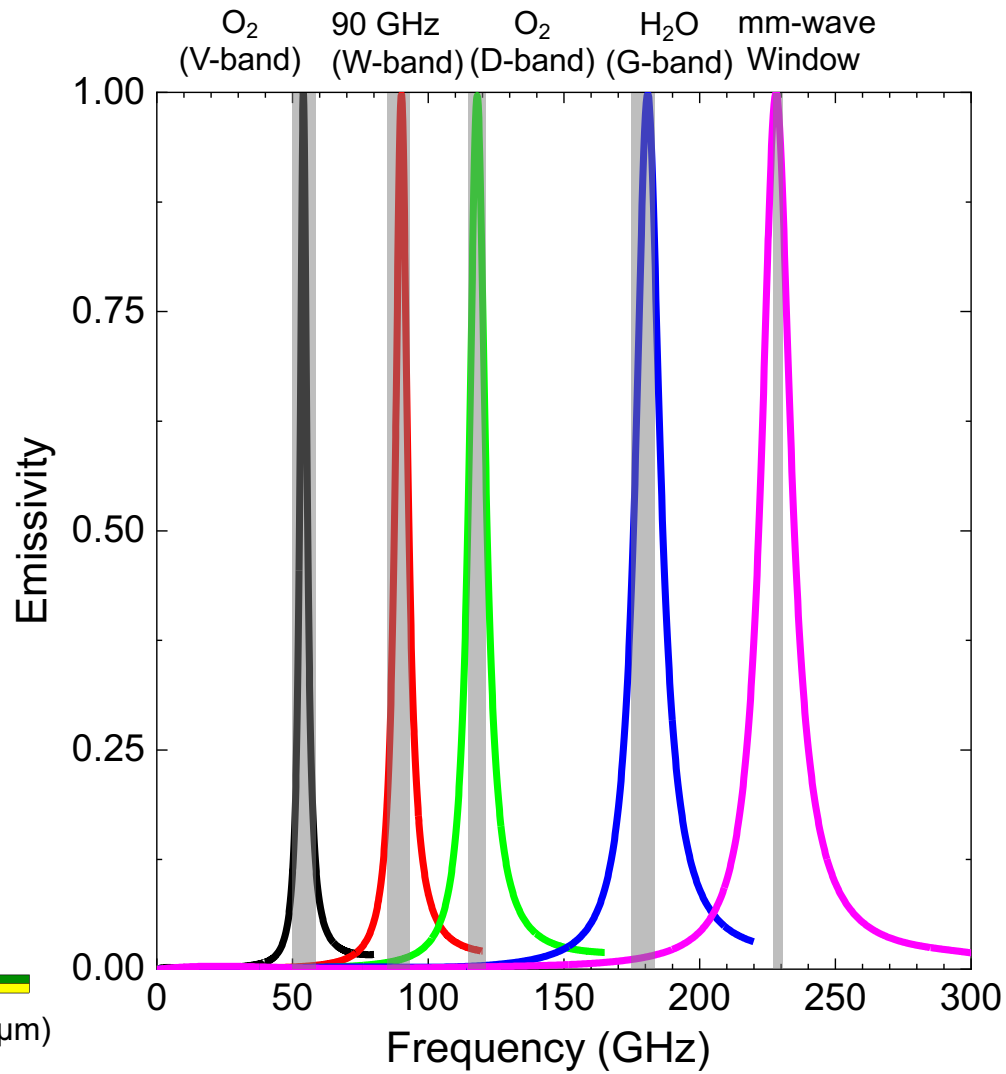
- PCB Calibration Target << mm thickness, weighing only ounces
- Improved thermal homogeneity for calibration
- Tailored frequency response defined by photolithographic features
- Simplified integration into planar/conformal structures

Design of Metamaterial Calibration Target

Metamaterials (MM) for calibration of millimeter-wave temperature and water vapor sounders and imagers

- *Electrodynamic similitude* – scaling operating frequency by scaling geometry
- Metamaterial emitters in the 50 – 230 GHz range
  - Thin ($t \approx \lambda_0/35$) and lightweight
  - Produced using PCB fabrication

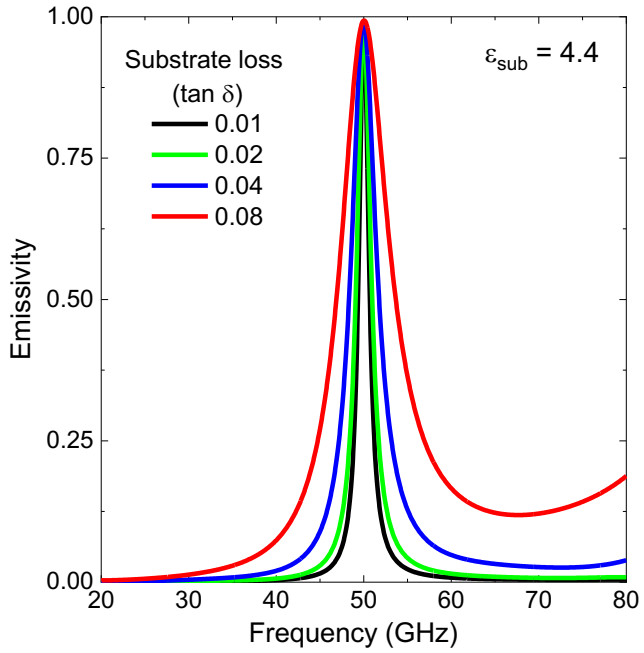




Metamaterial Design Improvements

Broadened bandwidth and multi-frequency emission

Increase material loss

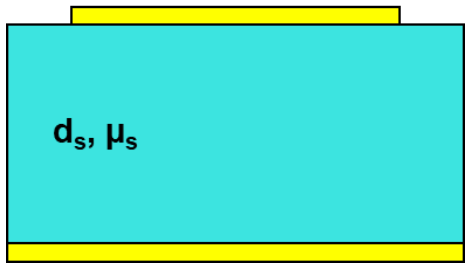


Fundamental BW-thickness limit

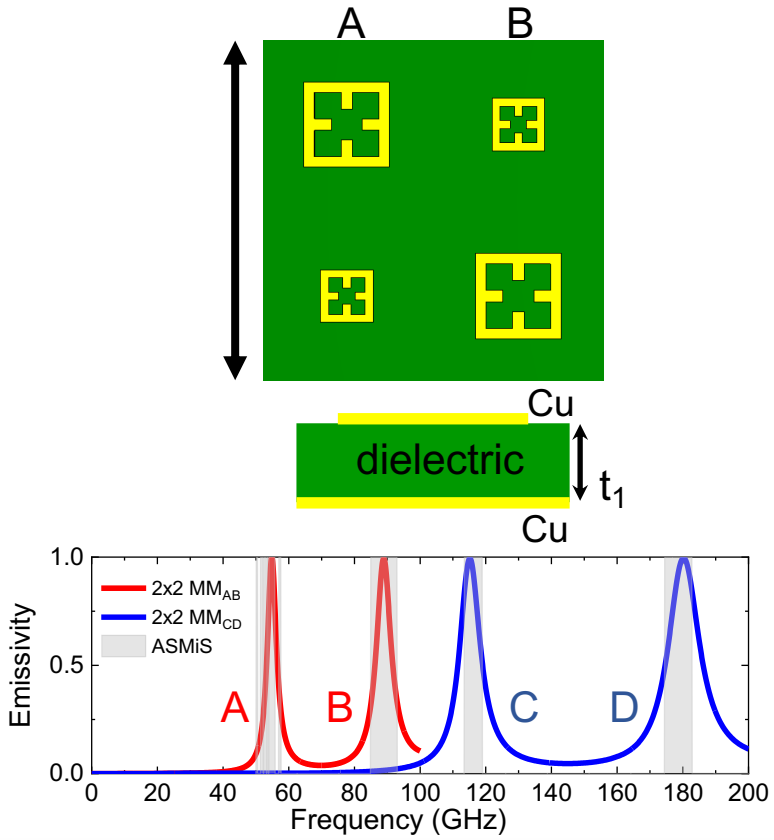
Rozanov Limit:

$$d_{min} = \frac{1}{2\pi^2 \mu_s} |\ln \rho_{min}| (\Delta\lambda)|$$

MM Side view



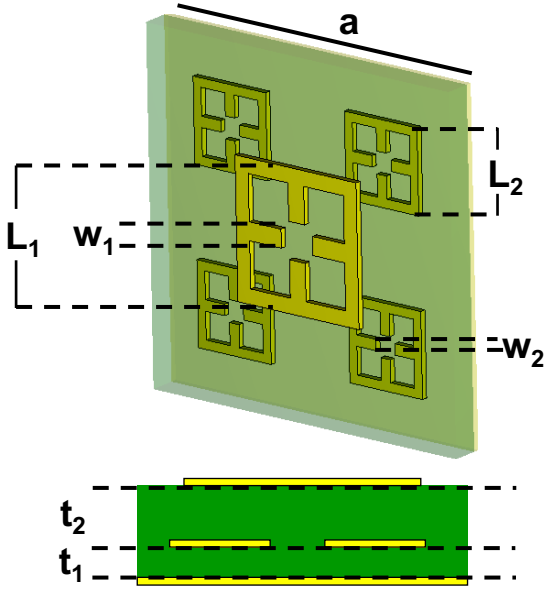
Supercell geometries



Machine Learning for Metamaterial Design

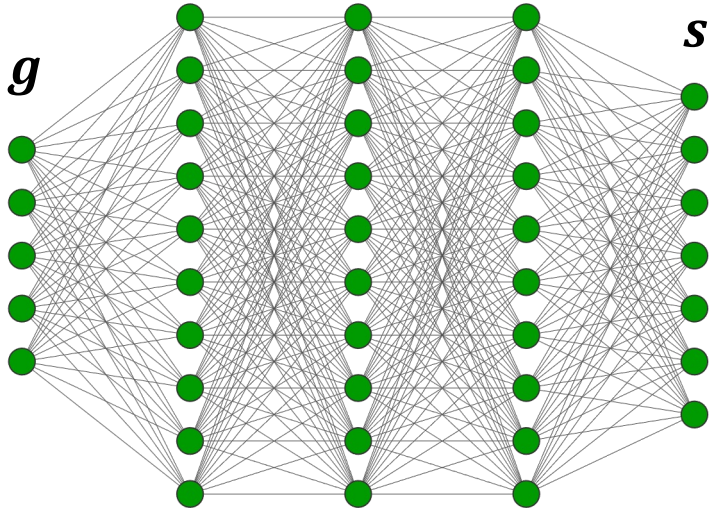
Deep neural networks (DNN) for metamaterial supercell emitter design**

Input: geometry *g*

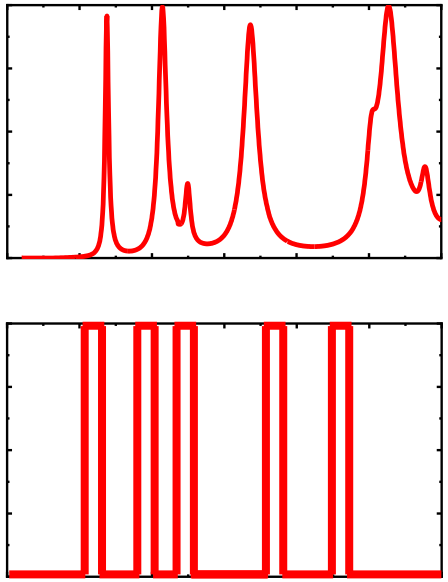


$g = \{a, L_1, L_2, w_1, w_2, t_1, t_2, \ldots\}$

Forward modeling: *g* → *s* (i.e. s = *f(g)*)



Output: emissivity spectrum *s*



Desired emissivity spectrum *s**

Inverse design: *s** → *g**

g*?

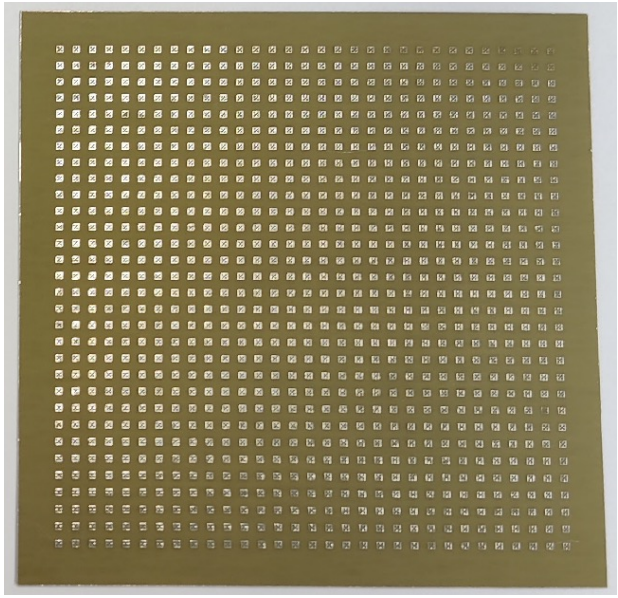
Data-driven approach (~10^4 simulations for DNN training)

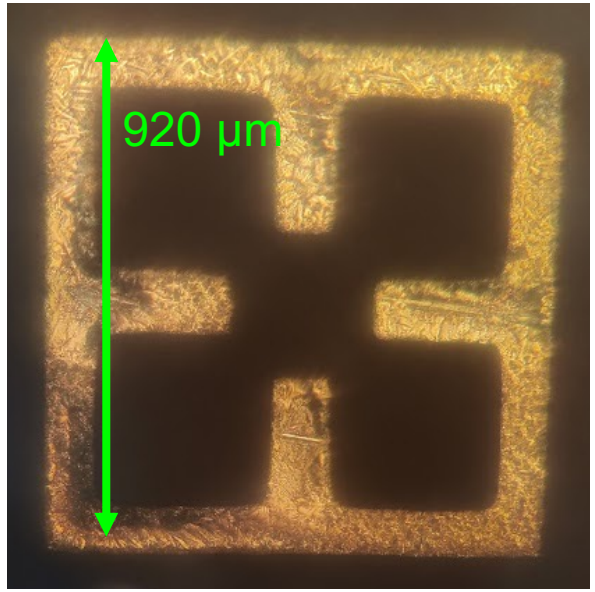
C.C. Nadell et al. Optics Express **27, 27523 (2019); *S. Ren et al., NeurIPS-2020; Y. Deng et al., Optics Express **29**, 7526 (2021); O. Khatib et al., Adv. Funct. Mater. **2021**, 2101748*

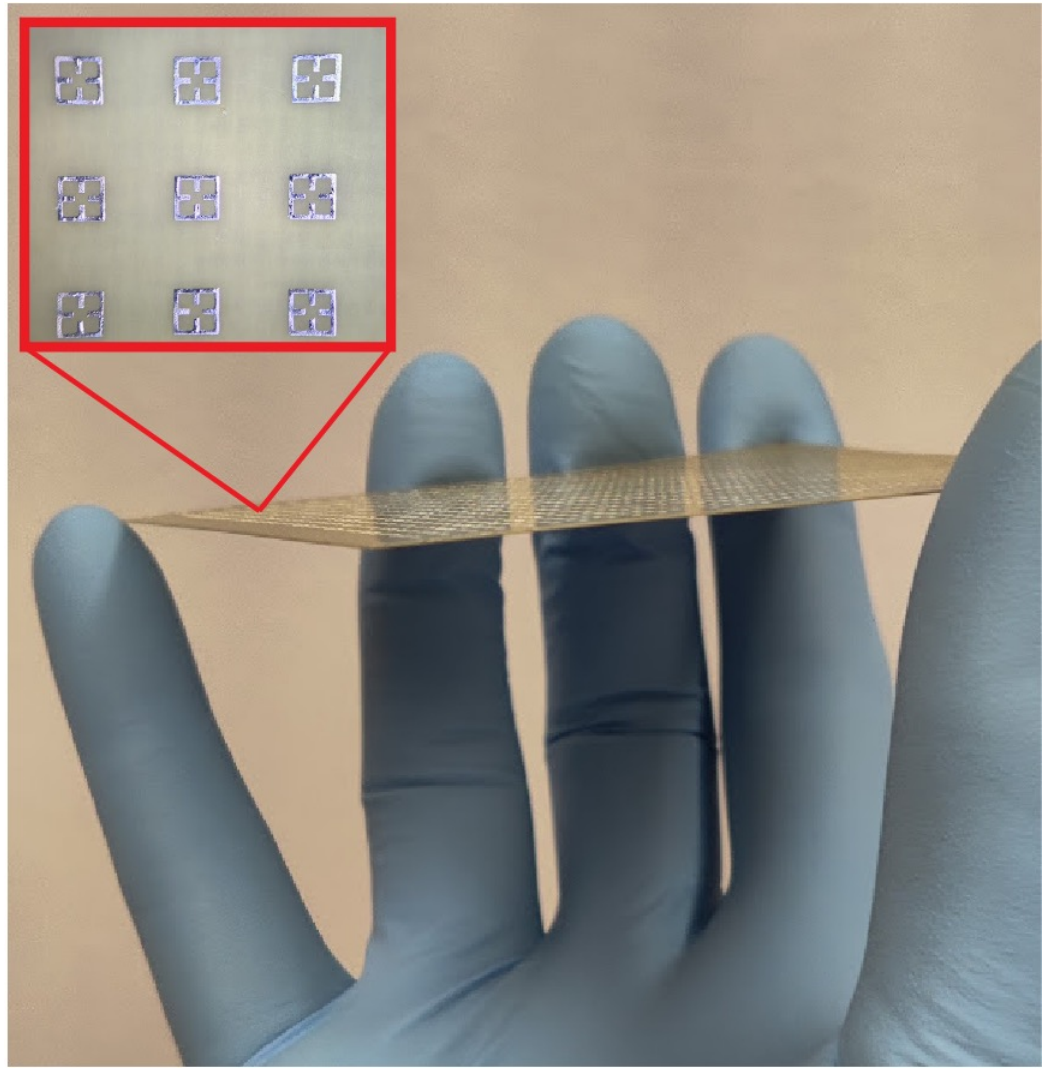
Metamaterial Target Fabrication

- Initially used commercial PCB manufacturing technology → easy and cost-effective to fabricate
- 10 PCB boards < $1500
- Initial design frequency: 54 GHz (31 x 31 unit cells)
- 8 cm x 8 cm board with extensible dimensions

8 cm

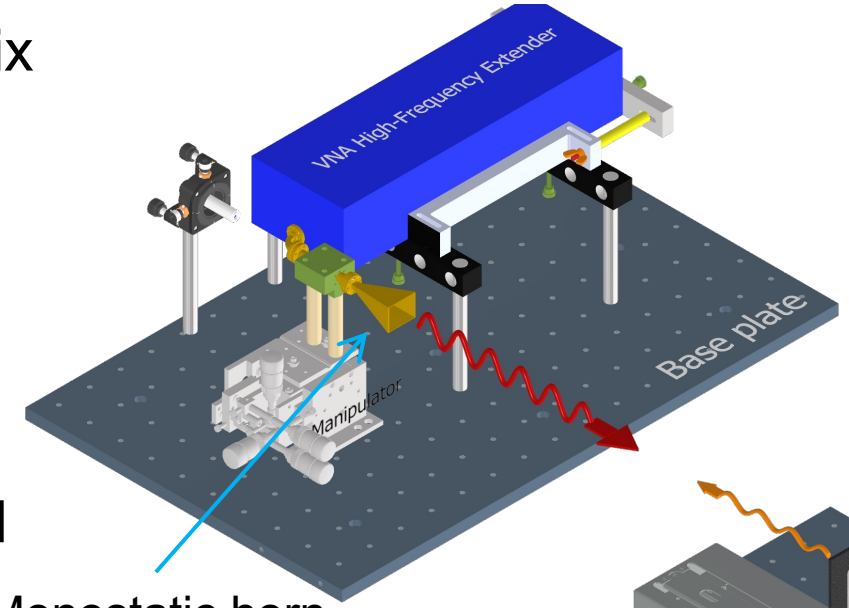






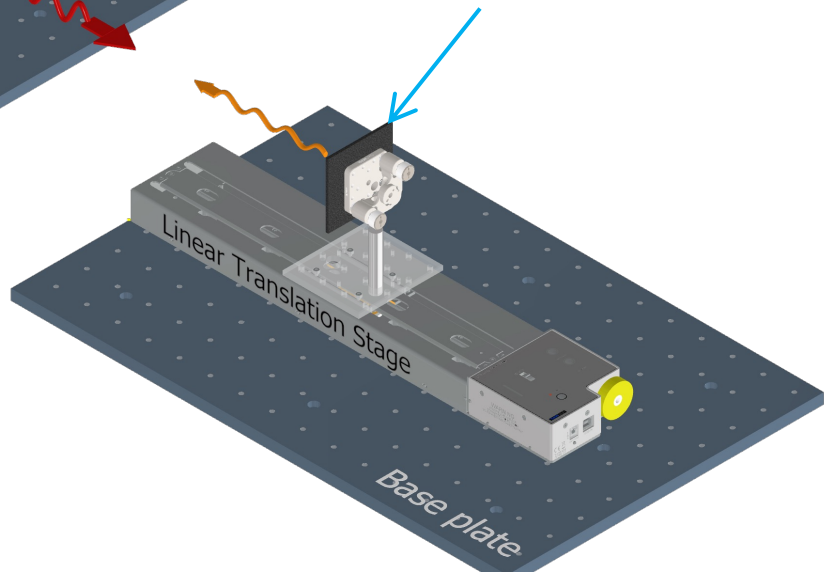
Validation using Free-Space mm-Wave Reflectivity Measurements

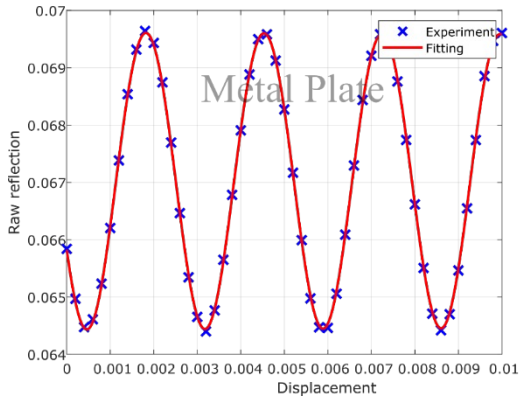
- Model with plane-wave scattering matrix theory
- Use reflectivity measurements to infer emissivity: $E = 1 - R$
- Implement with monostatic measurement apparatus
- Streamlined and automated broadband VNA reflection measurements

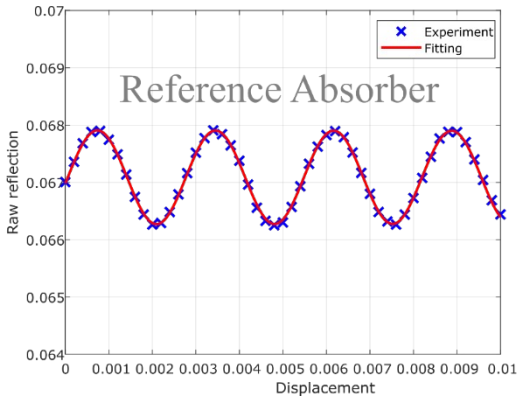


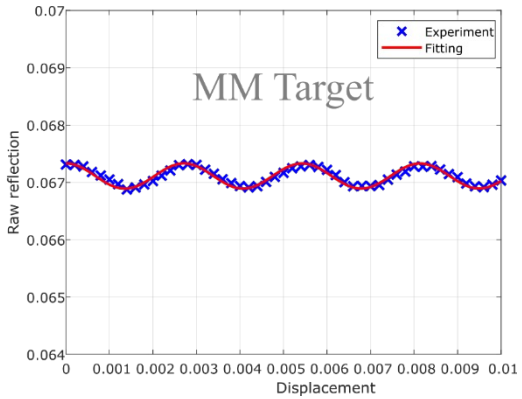
Monostatic horn antenna

Metamaterial Target



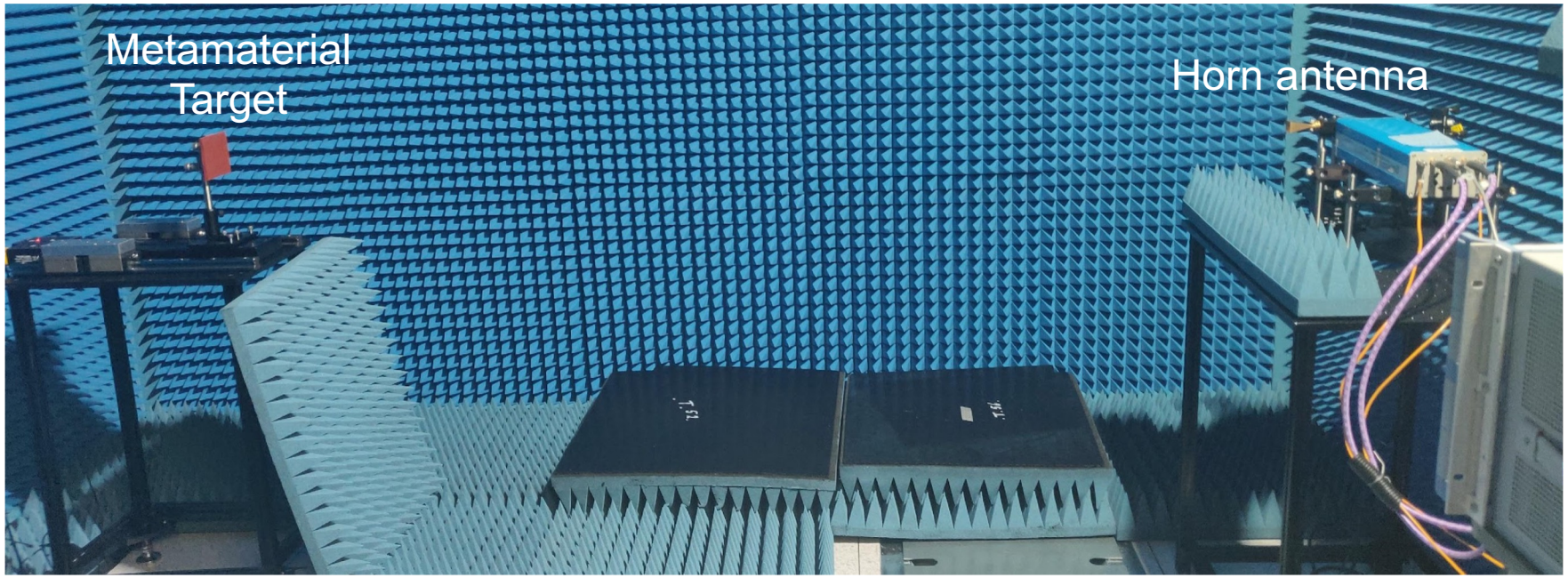






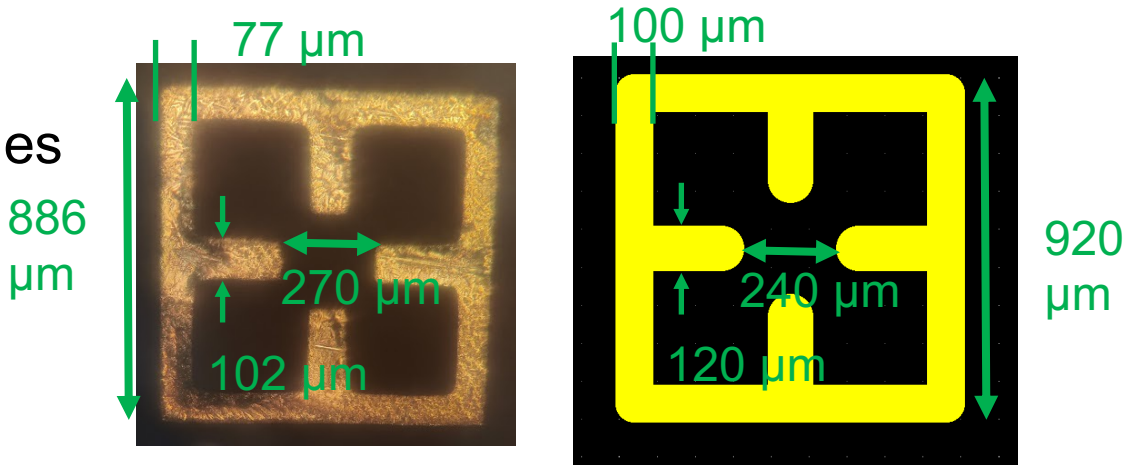
Anechoic Chamber Measurements at NIST Boulder

- NIST anechoic chamber 2.3 m x 2.4 m x 3 m, ~150 dB isolation.
- Vector network analyzer (VNA) with frequency extenders up to 220 GHz.
- Linear translation stage: 30 cm travel range and 2 μm repeatability.



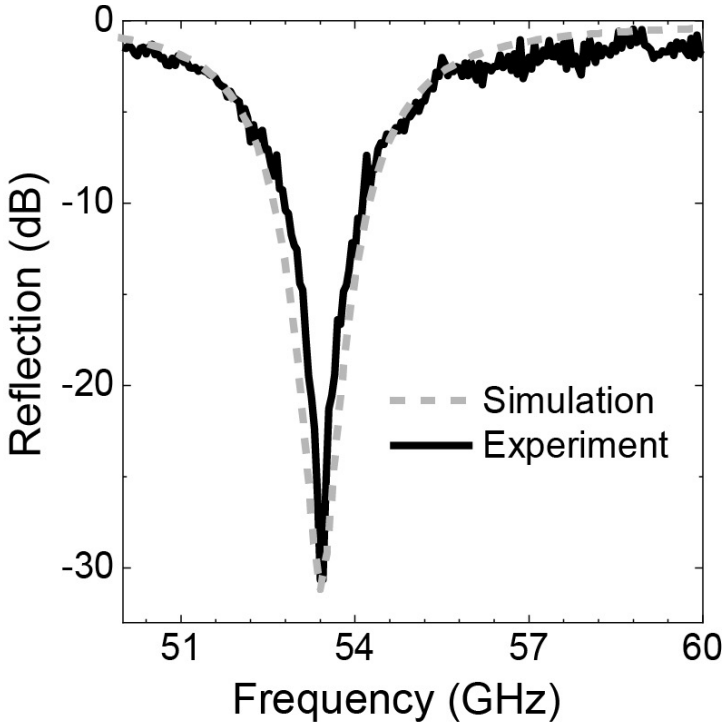
Comparison of Simulated and Measured Metamaterial Targets

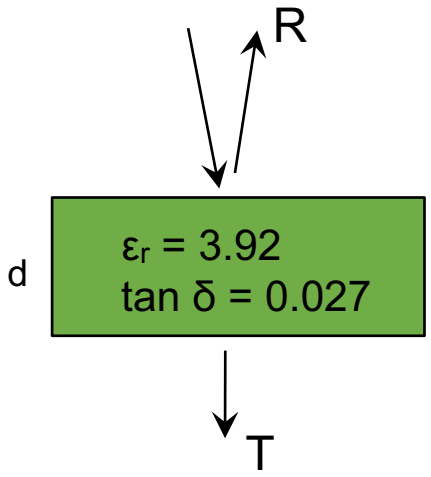
- Metamaterial sample dimensional metrology
- Characterized FR4 substrate mm-wave properties
- Re-simulated metamaterial response based on experimental data and metrology

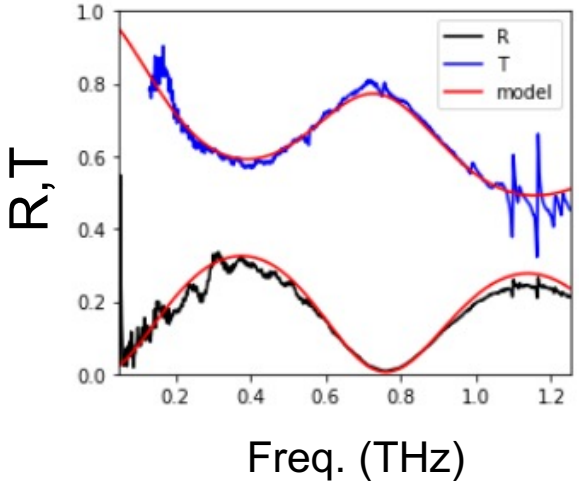


Isola 370R FR4 (samples from Hughes Circuits)

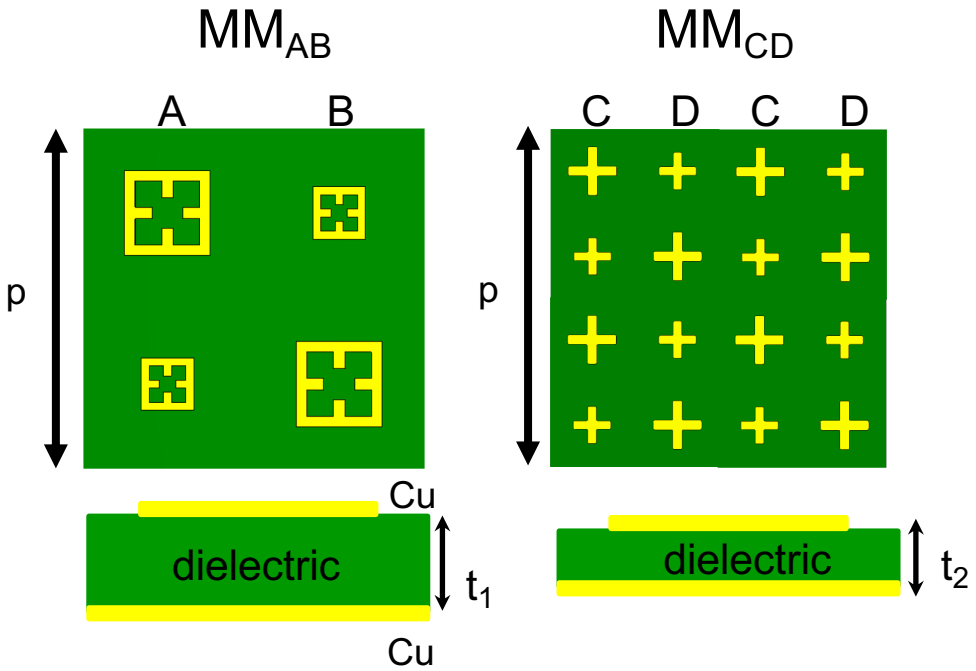
Very good agreement between simulations and NIST measurements!



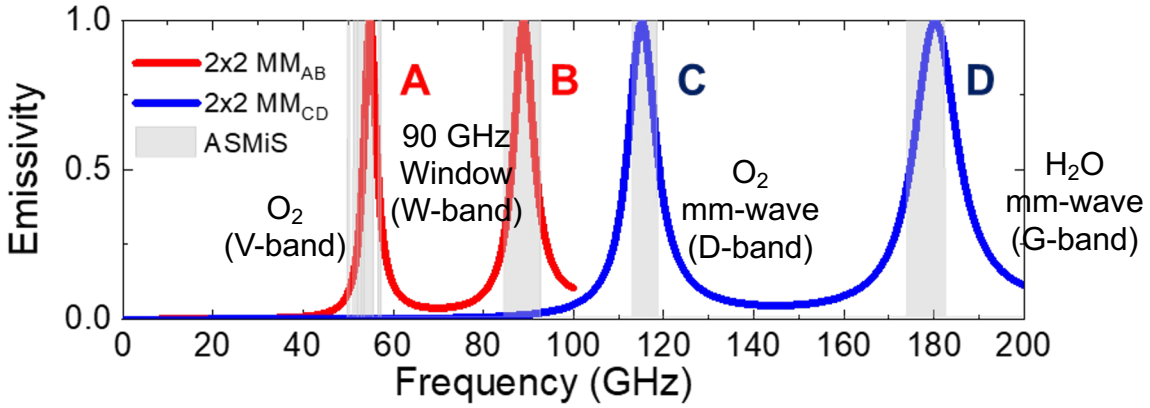




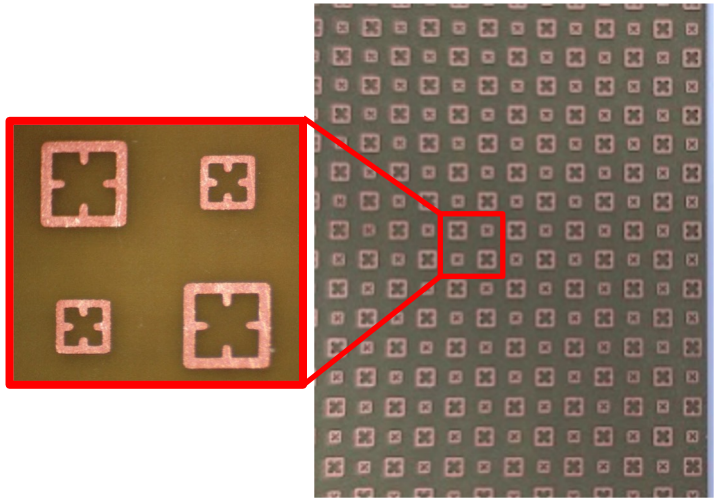
Metamaterial Supercell Targets

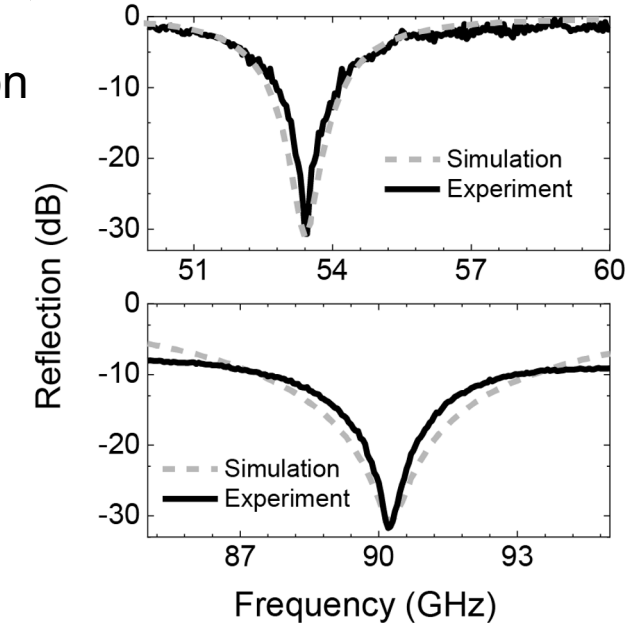


Simulated emissivity of 2 x 2 single-layer supercell targets



MM$_{AB}$ supercell characterization





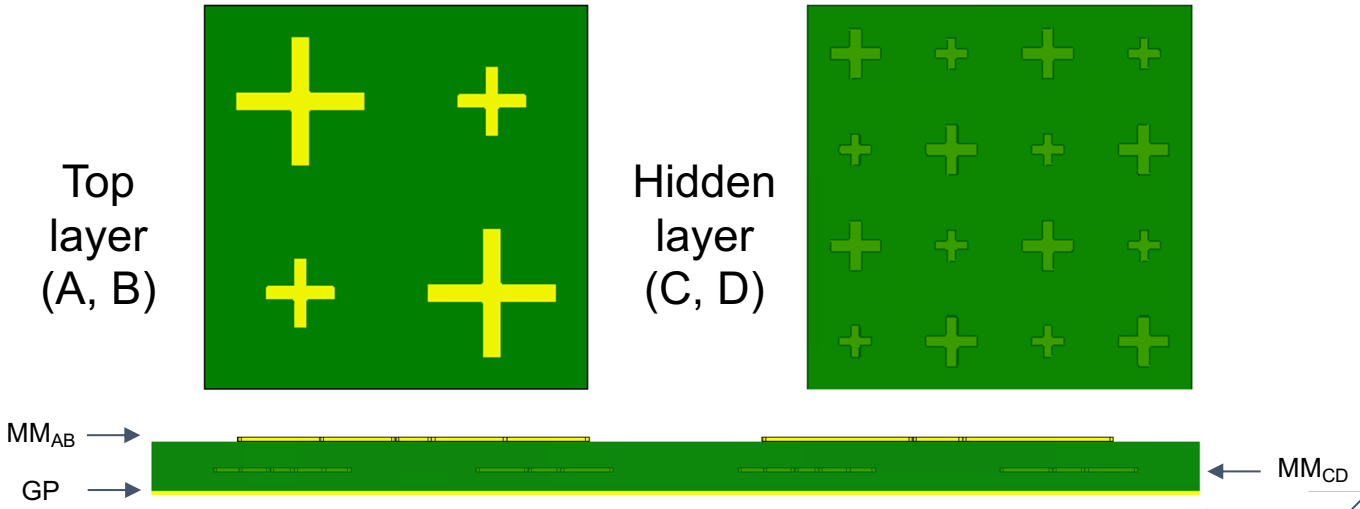
- Multiple bands arise from different single layers
- Fabricated MM$_{AB}$ target:

  Periodicity p = 1.6 mm

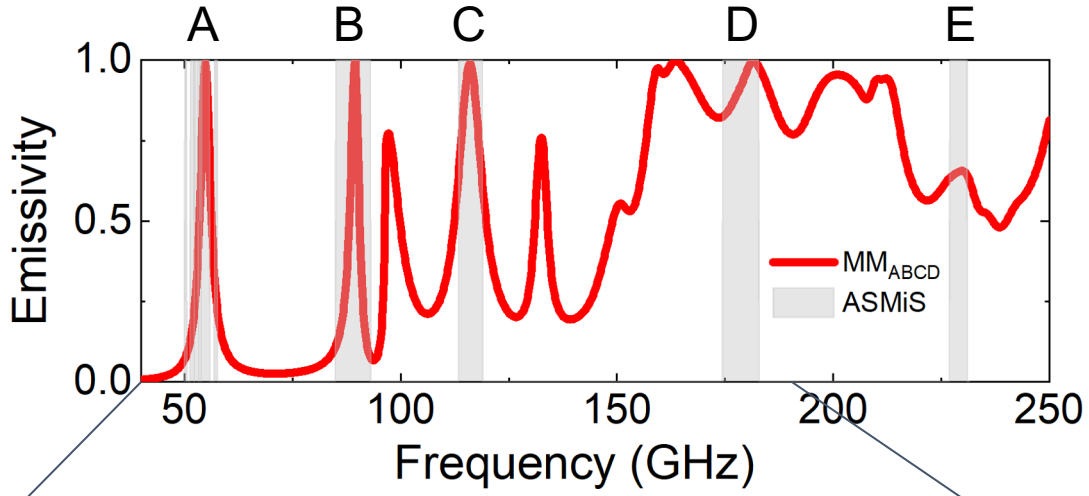
  50 x 50 unit cells in 8 x 8 cm^2

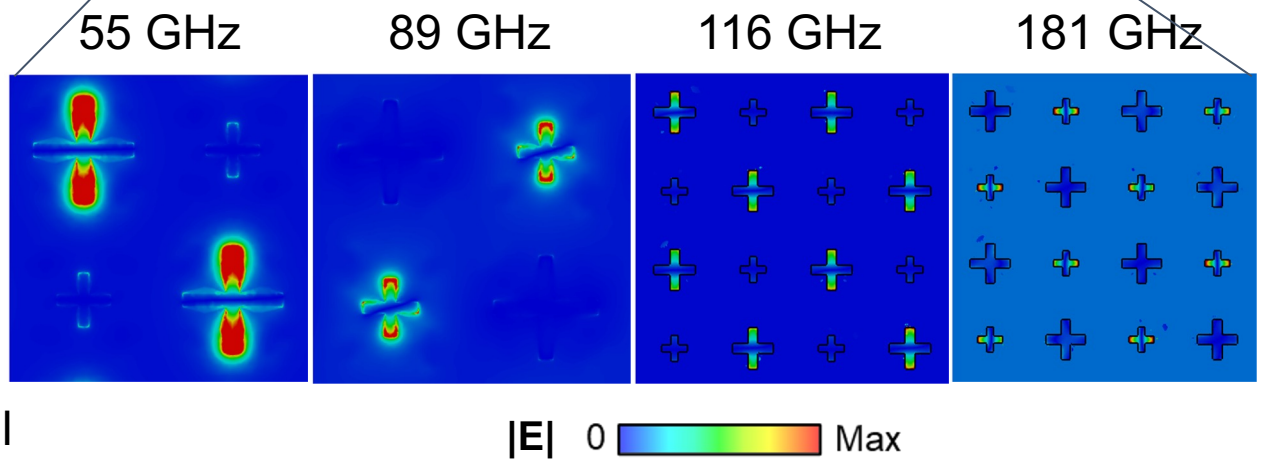
Multi-layer Four-Band Supercell Design

- Combined multilayer PCB supercell: MM_{AB} + MM_{CD}



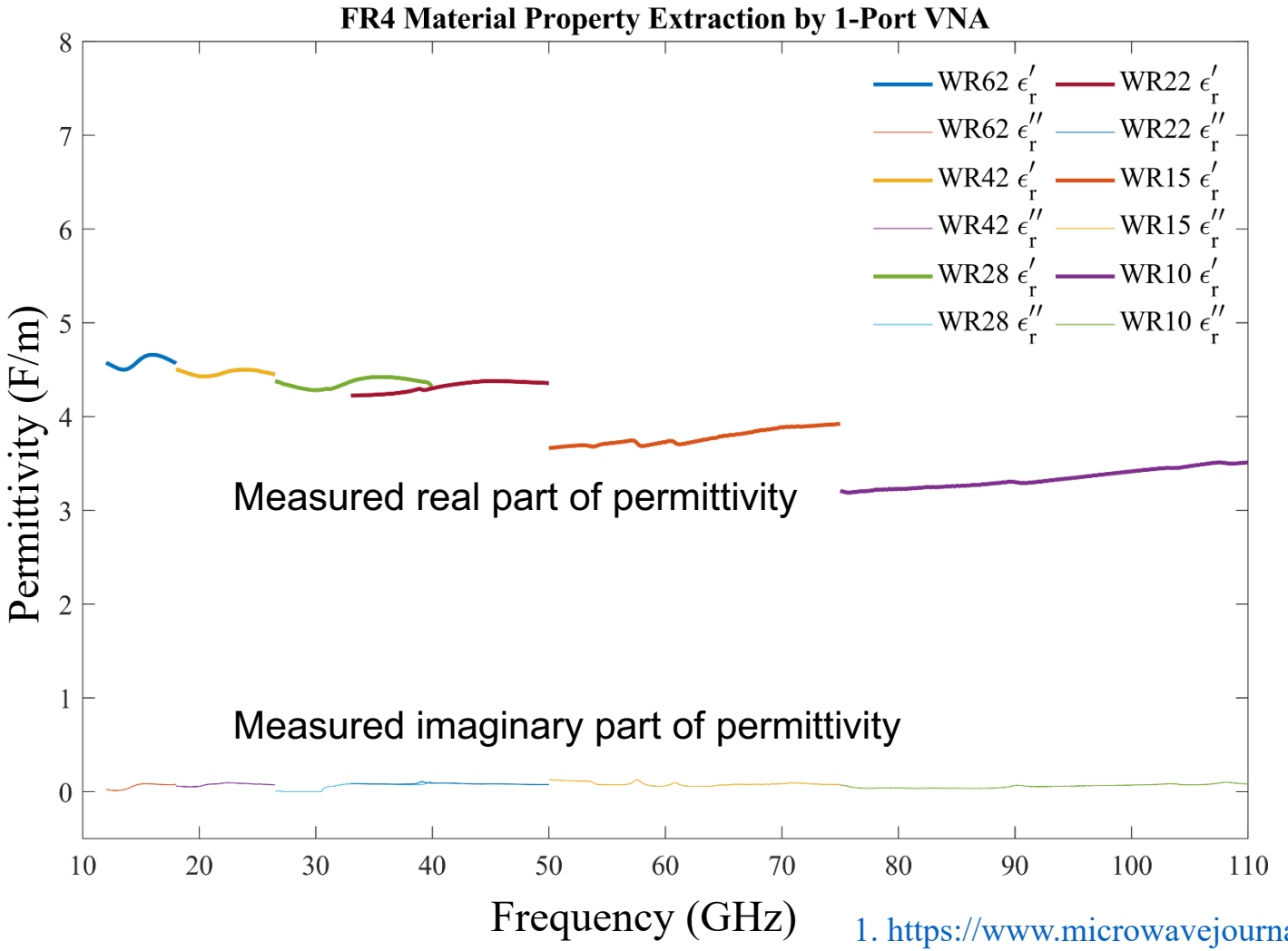
Simulated emissivity of multi-band PCB supercell



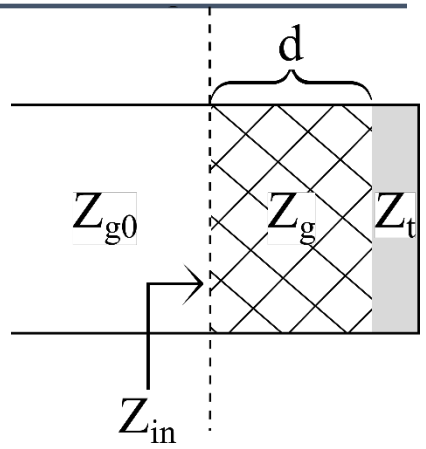


- Two-layer PCB metamaterial supercell for four-band operation
- Additional absorptions → higher-order modes
  - Need experimental feedback for broadband characterization
- Machine Learning → optimize multilayer supercell design, for high emissivity near 230 GHz (MM_E) as well

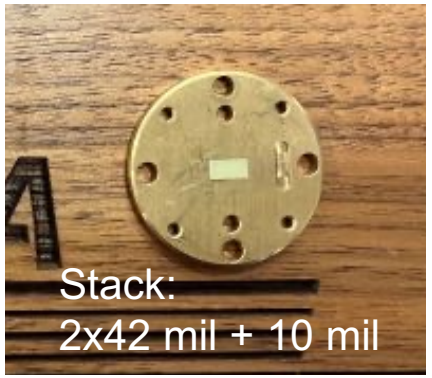
Waveguide Measurements of Complex Permittivity of FR4 Substrate



$$Z_{in} = Z_g \frac{Z_t + Z_g \tanh(\gamma d)}{Z_g + Z_t \tanh(\gamma d)}$$



FR4 in WR-22

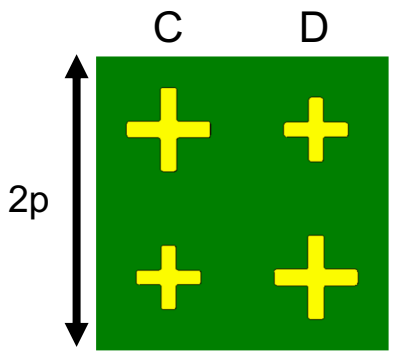


- Isola found that FR4 laminate "properties need to be fully tested across a range of resin contents, frequencies, constructions, using appropriate test methods."[1]
- Subsequent measurements at NIST confirmed anisotropy of FR4 substrates

1. https://www.microwavejournal.com/ext/resources/Webinars/2014/SLIDES_Isola_26feb14.pdf

Metamaterial PCB Target (MM_{CD})

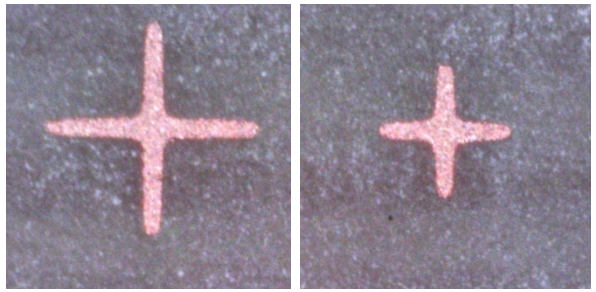
Design for calibration of mm-wave sounders of atmospheric temperature and water vapor near 118 and 183 GHz



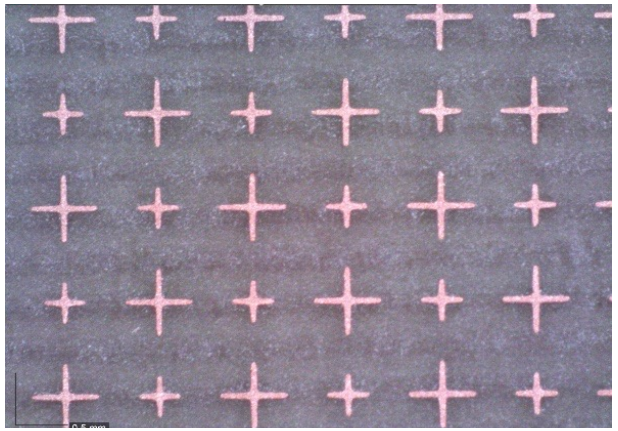
Side view

t_1 = 76 μm (3 mils)

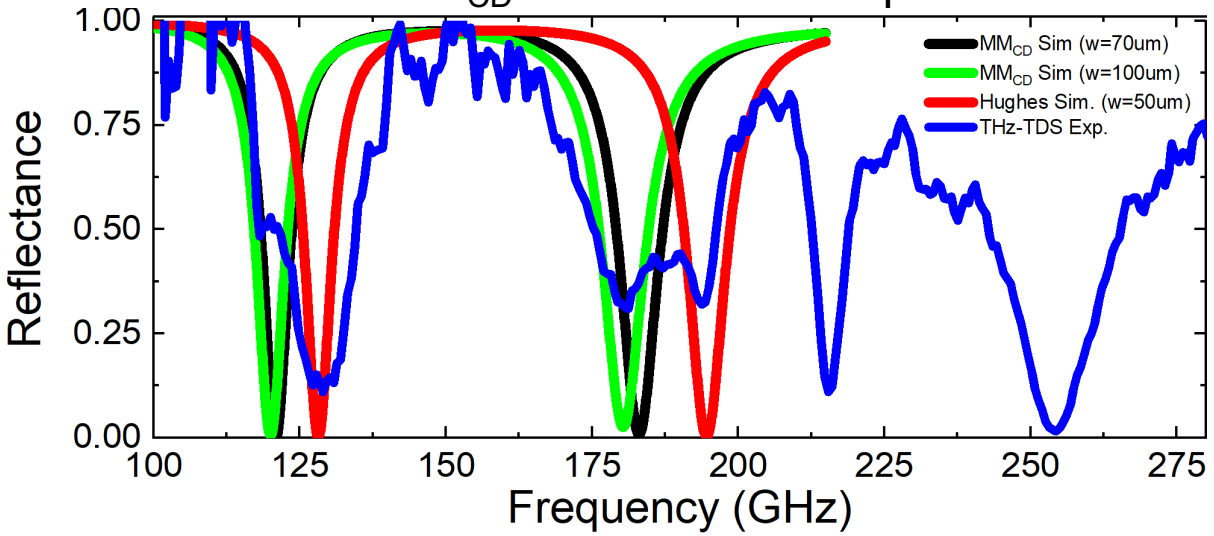
Microscopic image for detailed metrology:



MM_{CD} metamaterial calibration target



Simulation comparison based on updated metrology of fabricated MM_{CD} and THz-TDS experimental data

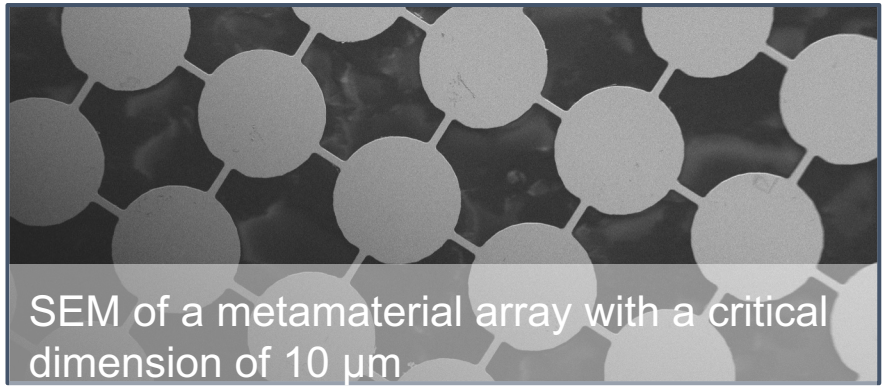


Metamaterial Target Nanofabrication Steps

Benefits of Nanofabrication:
- Pattern reproducibility
- Reliable material constants
- Smaller feature size (>2 μm)
- Smaller dimension tolerance

Contact photolithography (Karl Suss: MA6/BA6)

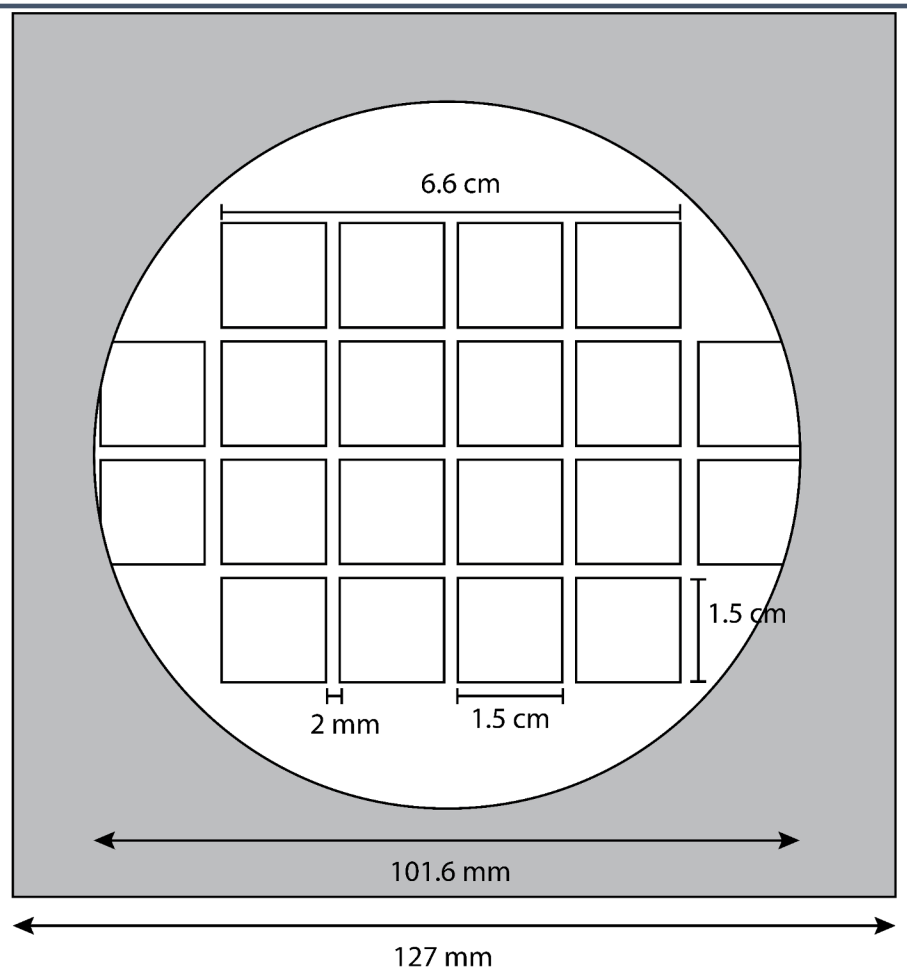
E-beam evaporation (CHA Industries: Solutions)



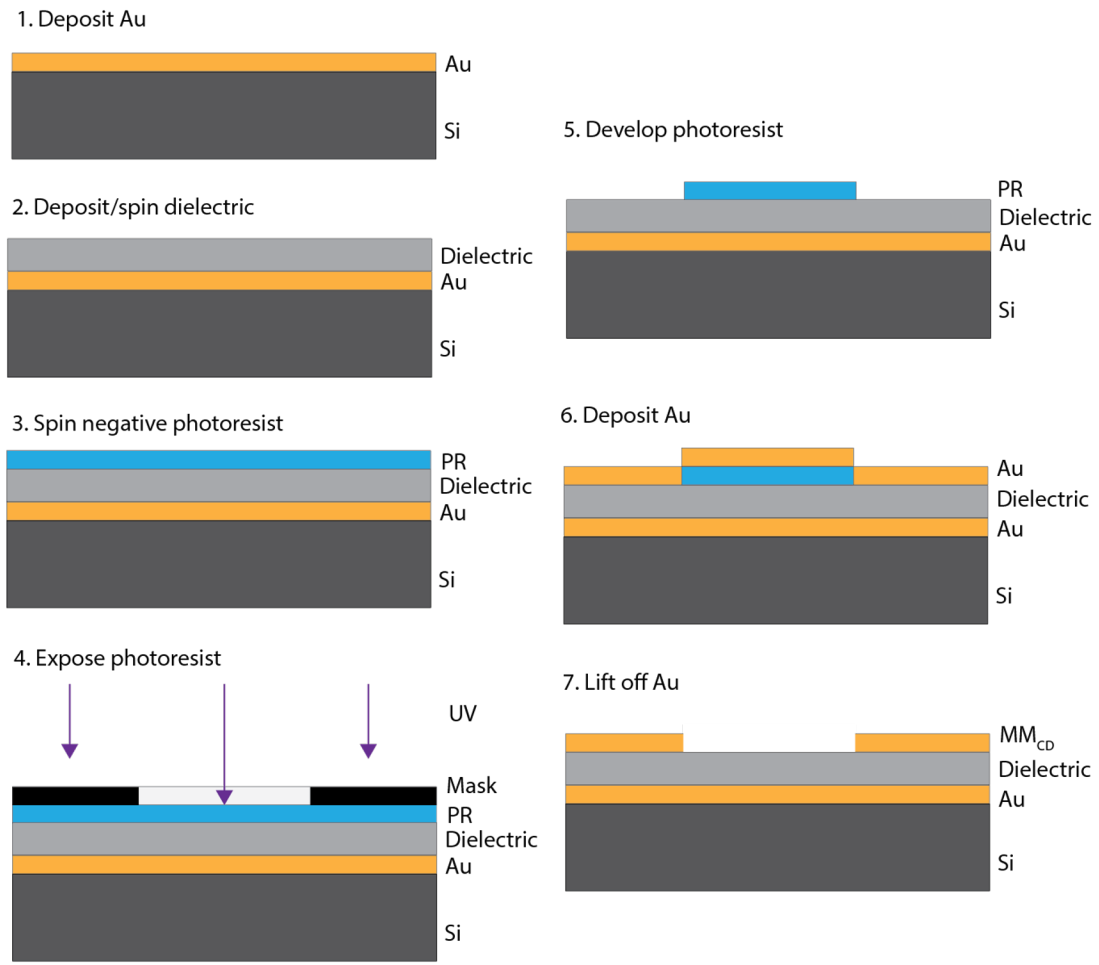
SEM of a metamaterial array with a critical dimension of 10 μm

Duke nanofabrication facilities

MM_{CD} Target Nanofabrication Steps



Example layout of a 10-cm circular exposure area, with 18 each of 1.5 x 1.5 cm metamaterial designs.



Fabrication steps for the MM_{CD} metamaterial using contact photolithography, metal deposition, and lift-off.

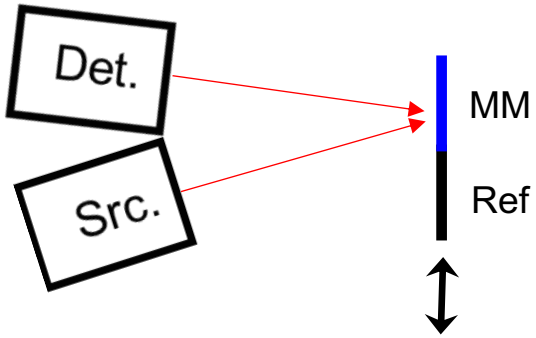
Thanks to the NASA Earth Science Technology Office for their support!

Backup Slides

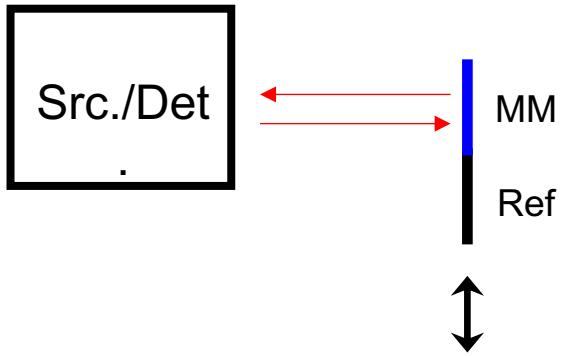
Experimental Validation

- Time-domain method (THz-TDS)
  - Broader bandwidth, more versatile (angular variation)
  - Less accurate, i.e. not as effective below 100 GHz
- Frequency-domain method (mm-Wave VNA measurements)
  - More accurate, reliable instrumentation
  - Segmented waveguide frequency bands, i.e. more time intensive

THz-TDS



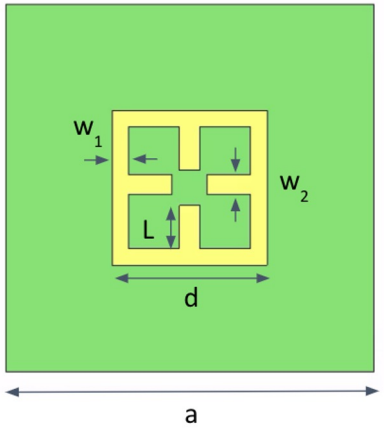
mm-Wave



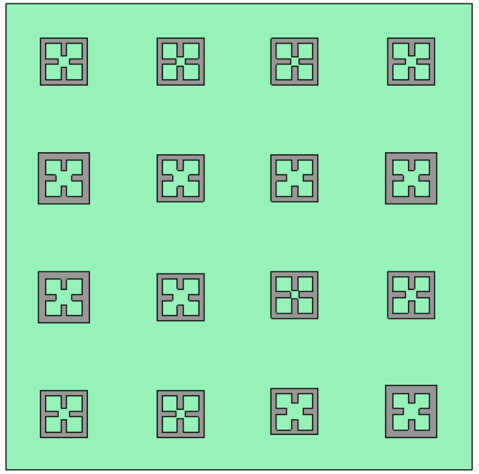
Increasing Metamaterial Bandwidth

Add random geometric variations to increase bandwidth of high emissivity

- Deliberately broaden peak emission frequency range
- Add “Gaussian noise” to unit cell geometrical parameters

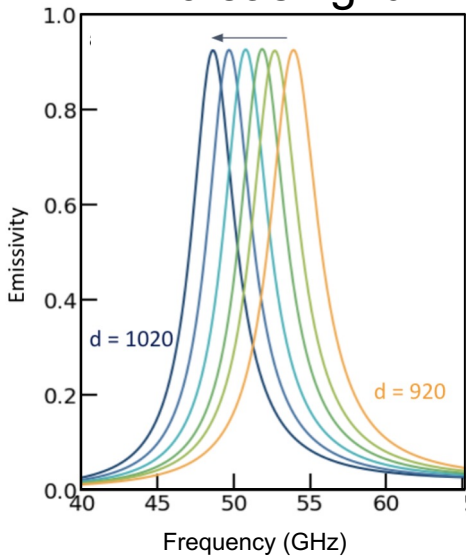


Simulated Results

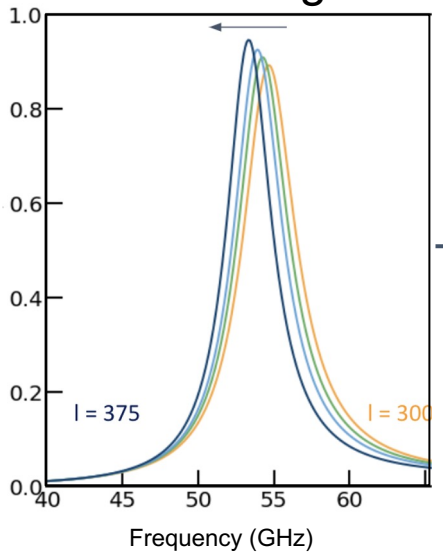


Unit cells with random geometric variations

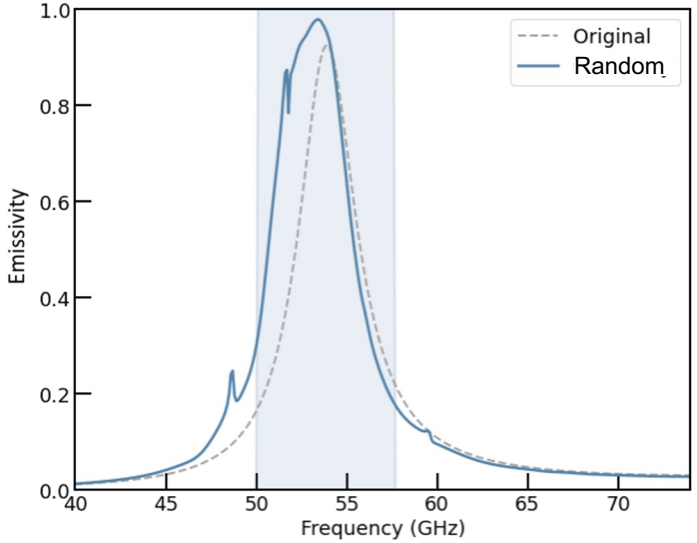
Increasing ‘d’



Increasing ‘L’



Electrodynamic similitude

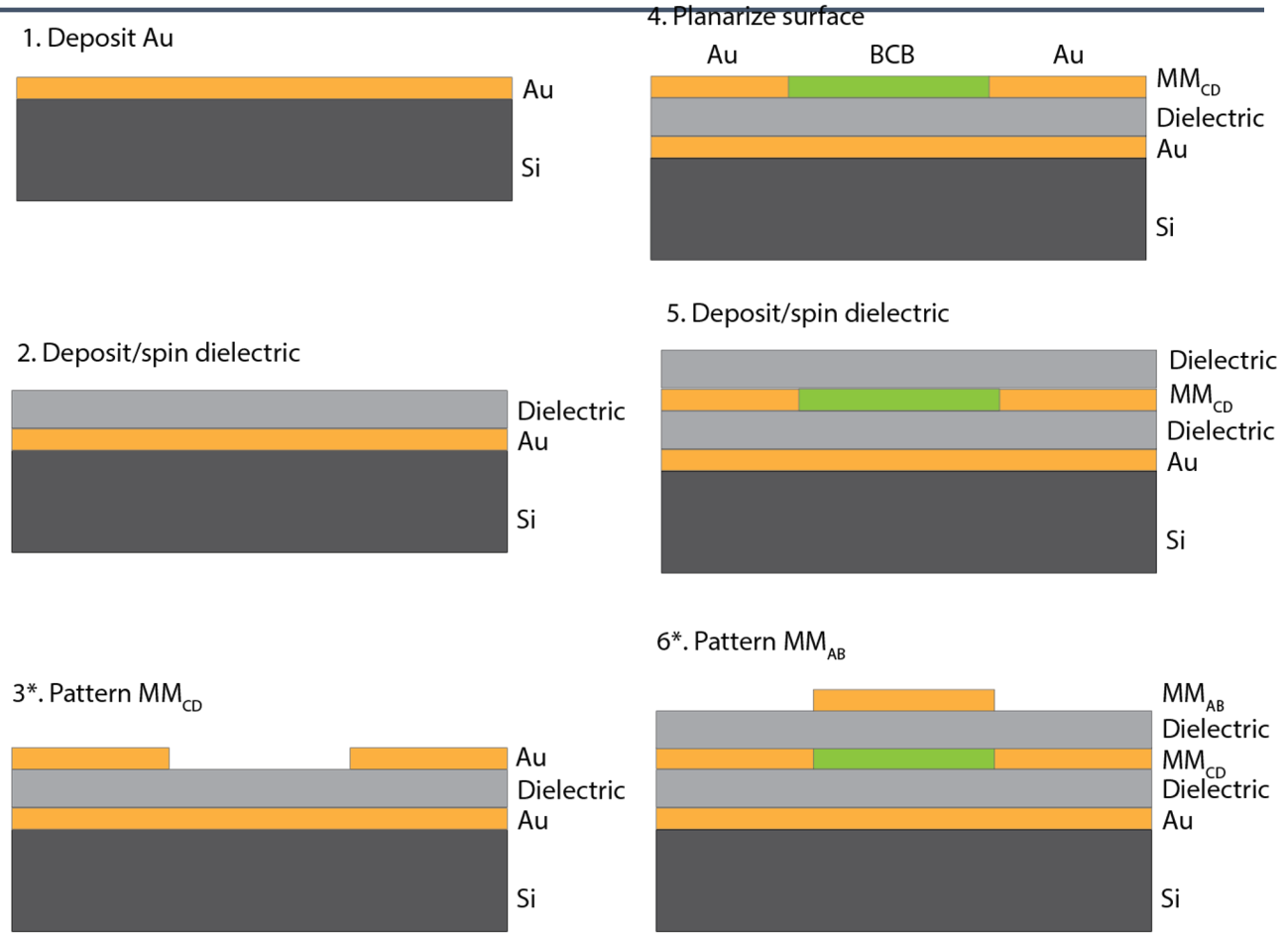


Increased bandwidth

MM_{ABCD} Target Fabrication Steps

Equipment and Chemical List:

- Karl Suss MA6/BA6 Frontside/Backside Contact Aligner
- 5” Cr on quartz photomask
- CHA Industries Solution E-Beam Evaporator
- Negative photoresist: NFR-016D2 (2.5 µm)
- Developer: MF-319
- Ultrasonic for lift-off



Fabrication steps for the MM_{ABCD} emitter using contact photolithography, metal deposition, and lift-off.