Department of Electrical, Computer, Software and Systems Engineering

Enabling Wireless Structural Electronics and Sensors: *From Additively Manufactured mm-Wave Circuits to Novel Sensing Mechanisms*

Eduardo Rojas-Nastrucci[1], Thomas Weller[2], William C. Barott[1], Daewon Kim[1], and Sirish Namilae[1]

[1]Embry-Riddle Aeronautical University, Daytona Beach, FL, 32114. E-mail: e.rojas@erau.edu, kimd3c@erau.edu, namilaes@erau.edu

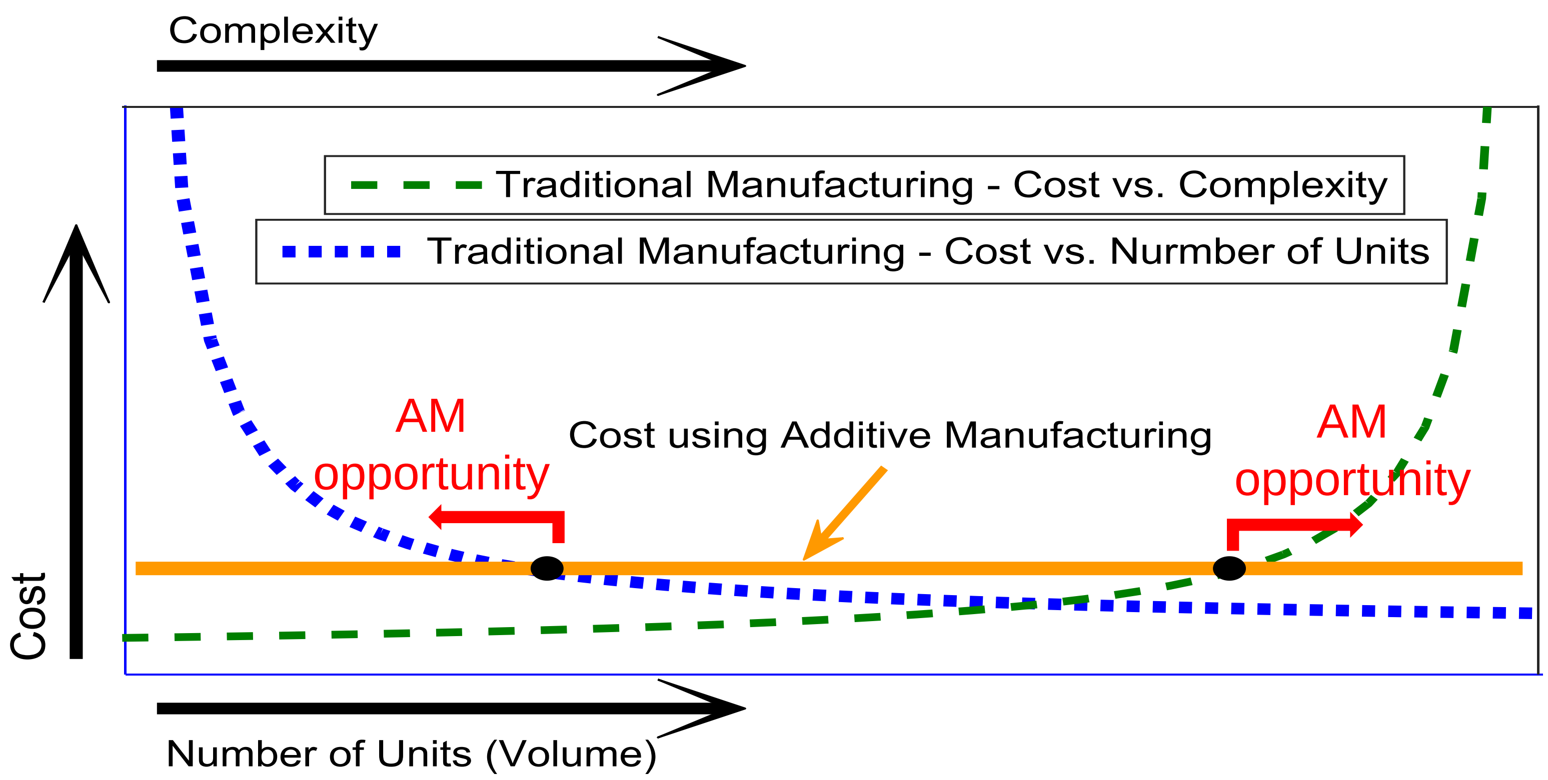
[2]University of South Florida, Tampa, FL, 33620. E-mail: weller@usf.edu

www.wide-lab.com

Agenda:

- ✓ *Introduction*
- ✓ *DDM Process (Additive Manufacturing)*
  - *- Multilayer RF Electronics*
- ✓ *Laser Enhanced DDM*
  - *- 3D Component Packaging*
  - *- mm-Wave Multilayer Circuit*
- ✓ *Sensing Mechanism for Micro Meteorite Orbital Debris (MMOD) Impacts*
- ✓ *ERAU Capabilities. Micaplex. WiDE Lab*

Introduction



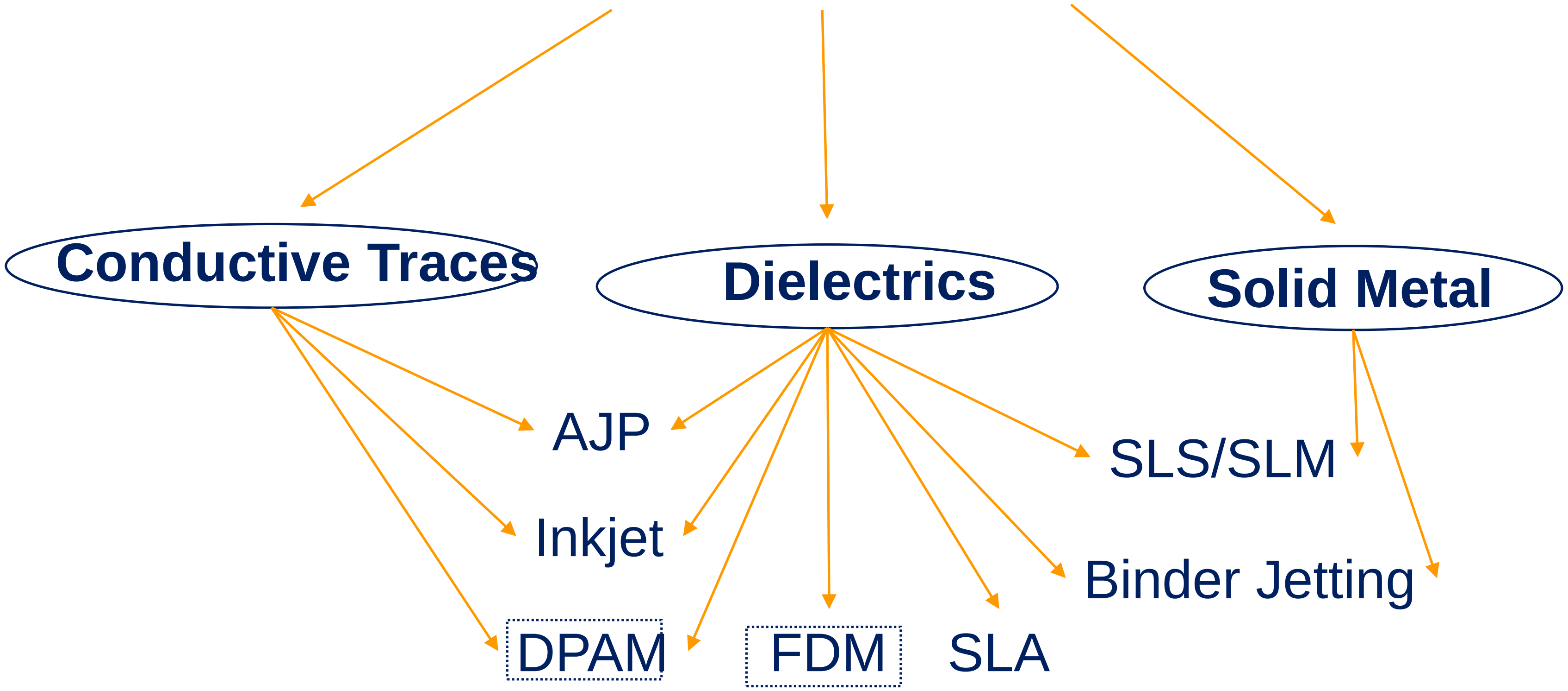
3D Printed Fuel Nozzle
by General Electric.

Improved Design:
25% lighter
5x stronger
Substitutes 18 parts

http://www.gereports.com/post/116402870270/the-faa-cleared-the-first-3d-printed-part-to-fly/

Simpler designs are less costly and better **– Not true with AM**

3D Printing Technologies
RF Circuits and Antennas



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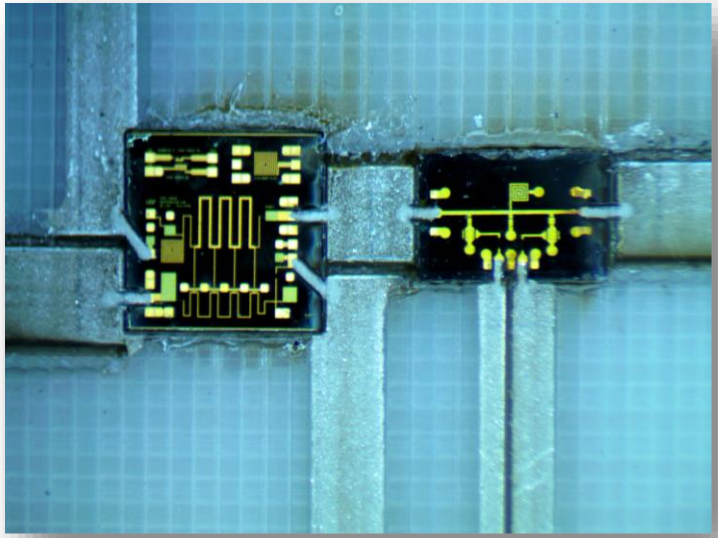
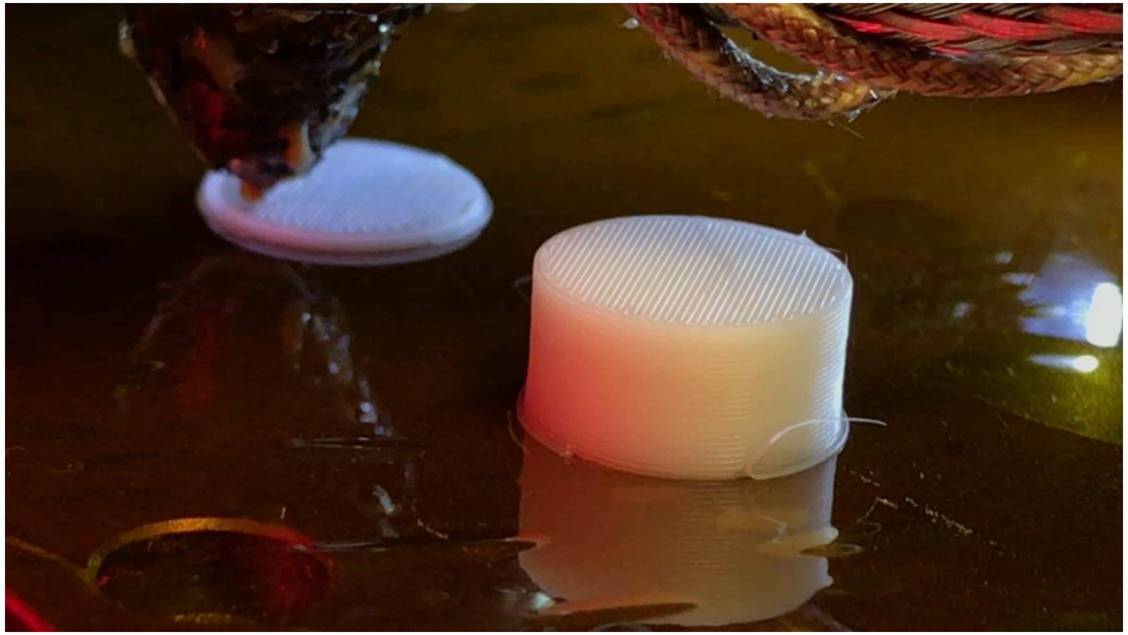
Introduction

- Direct Digital Manufacturing (DDM): Combination of additive and subtractive processes, *applied directly from CAD file to part*.
- This work: combination of FDM, micro-dispensing and laser machining.
  - Multiple materials, multiple layers.
  - Low temperature.
  - Match performance of Cu-clad microwave laminates.
  - Embed/integrate/package microelectronics.
  - Volumetric control of materials.



DDM Process: *FDM*

Video:



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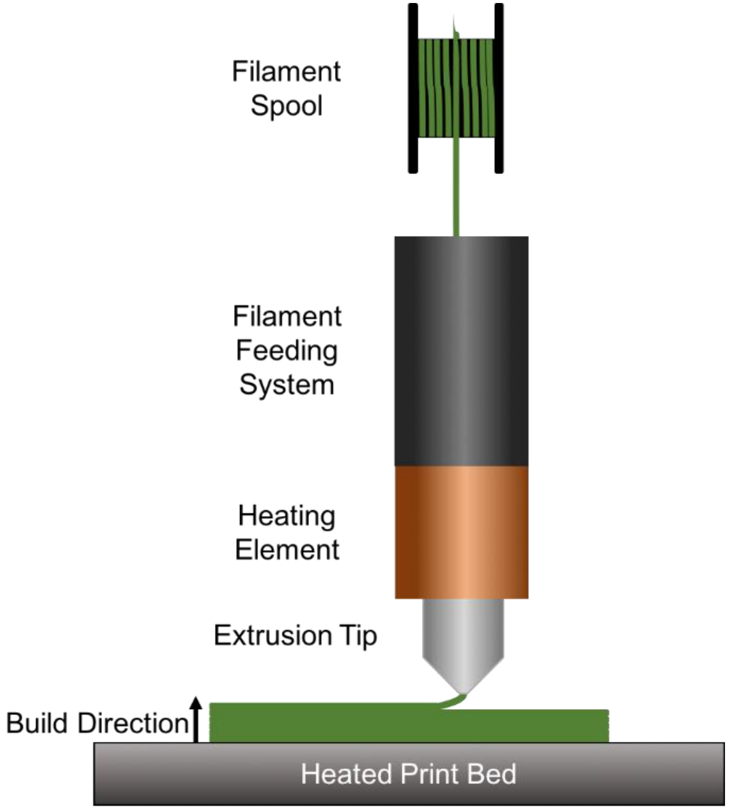


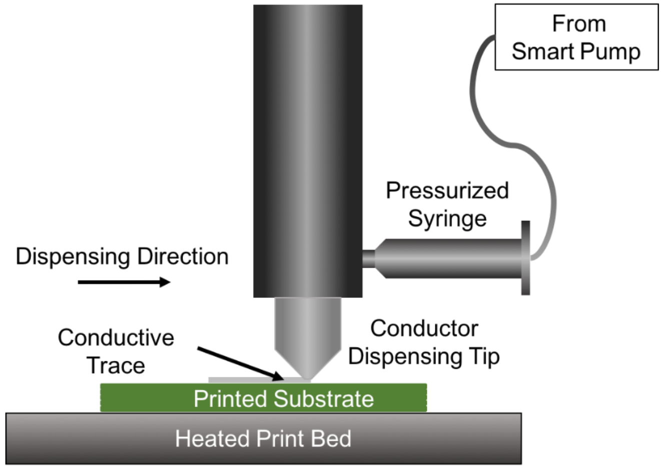
Typical nozzle temperature 200°C –350°C
Minimum layer thickness ~50 microns

DDM Process: *Micro-Dispensing*

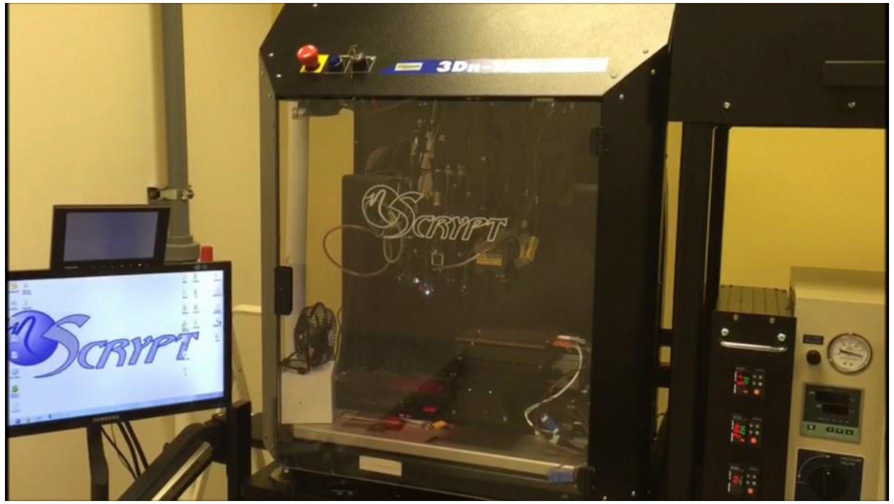
- Pastes such as Ag particle alloys used for conductors

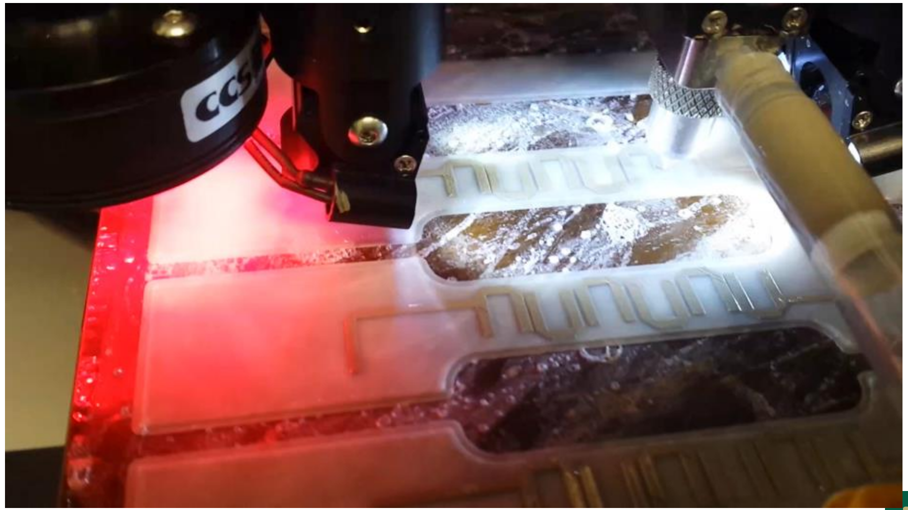
- Pressure, speed, etc. adjusted for desired feature sizes

- Conformal printing using laser mapping



Tip inner diameters:
250µm
125µm
75µm
25µm



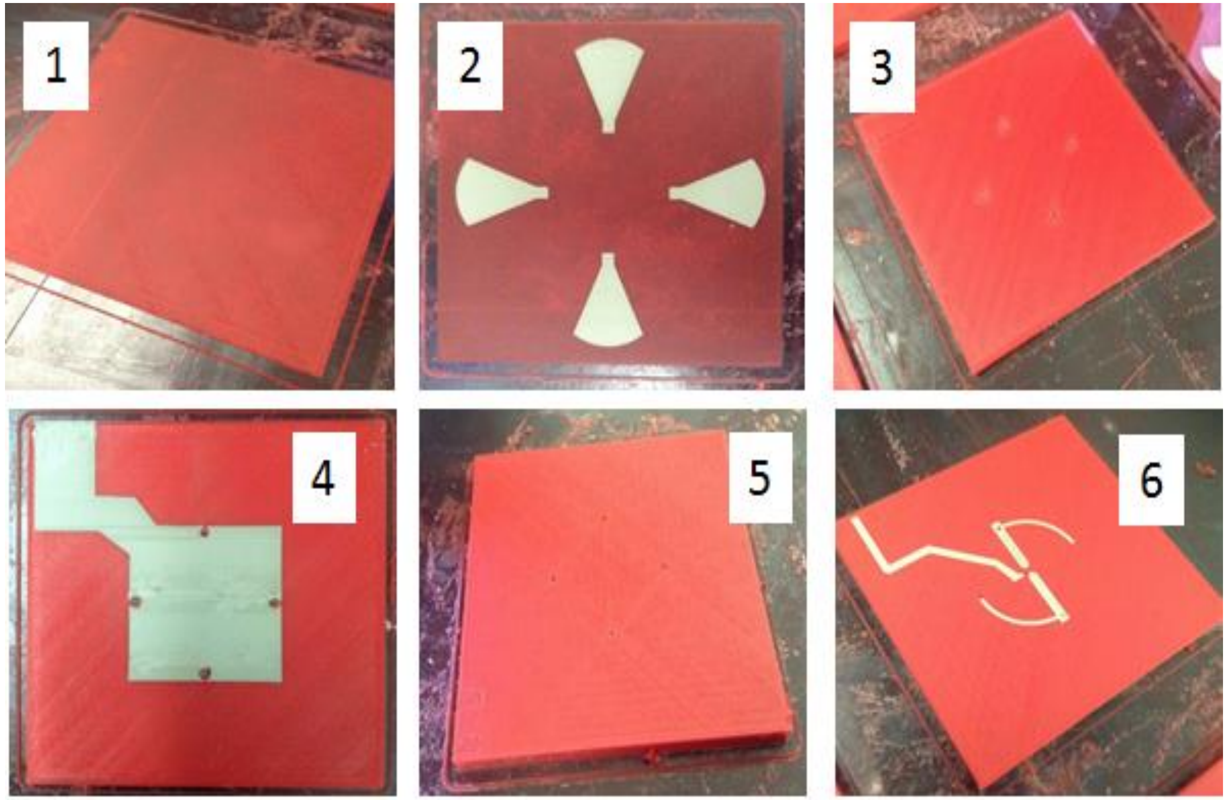


https://drive.google.com/open?id=0B0lhQblCdUwJU0t6U3A2NGlBazA

DDM Process: *Multi-Materials*

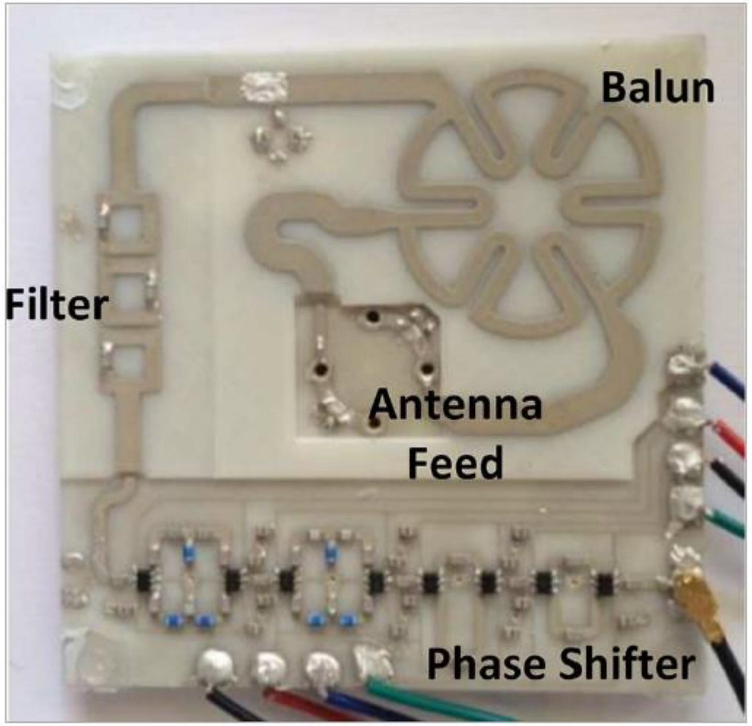
- Interleaving FDM and micro-dispensing

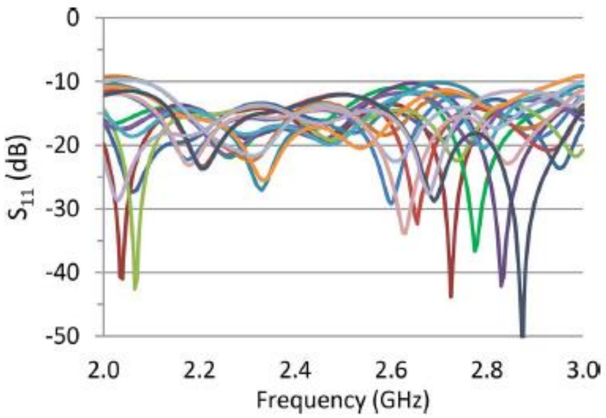
- Bed held at 90°C to cure Ag paste



Multilayer RF Electronics

2.45 GHz phased array antenna unit cell





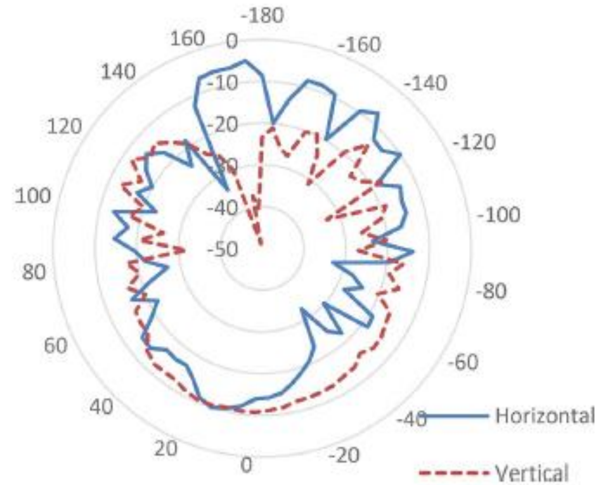


Fig. 24. Measured radiation patterns of the 2.45 GHz phased array unit cell. The vertical and horizontal gain pattern plots are shown.

Thomas P. Ketterl, Yaniel Vega, Nicholas C. Arnal, John W. I. Stratton, **Eduardo A. Rojas-Nastrucci**, María F. Córdoba-Erazo, Mohamed M. Abdin, Casey W. Perkowski, Paul I. Deffenbaugh, Kenneth H. Church, and Thomas M. Weller, "A 2.45 GHz Phased Array Antenna Unit Cell Fabricated Using 3-D Multi-Layer Direct Digital Manufacturing," in IEEE Transactions on Microwave Theory and Techniques, vol. 63, no. 12, pp. 4382-4394, Dec. 2015.

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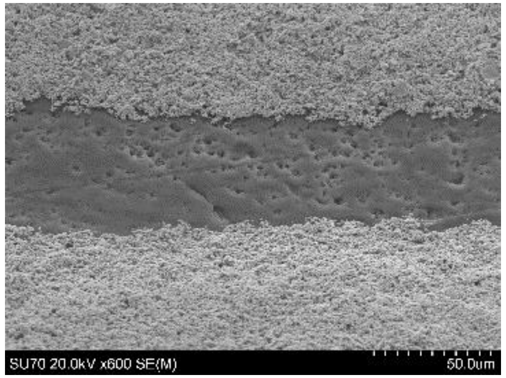
Multilayer RF Electronics

Video:

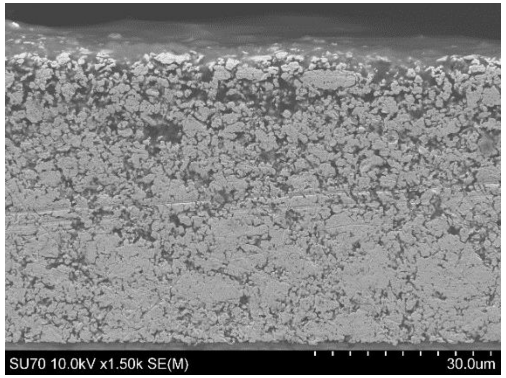
https://drive.google.com/open?id=0B0lhQblCdUwJQlEtZVIzSjZIV0k

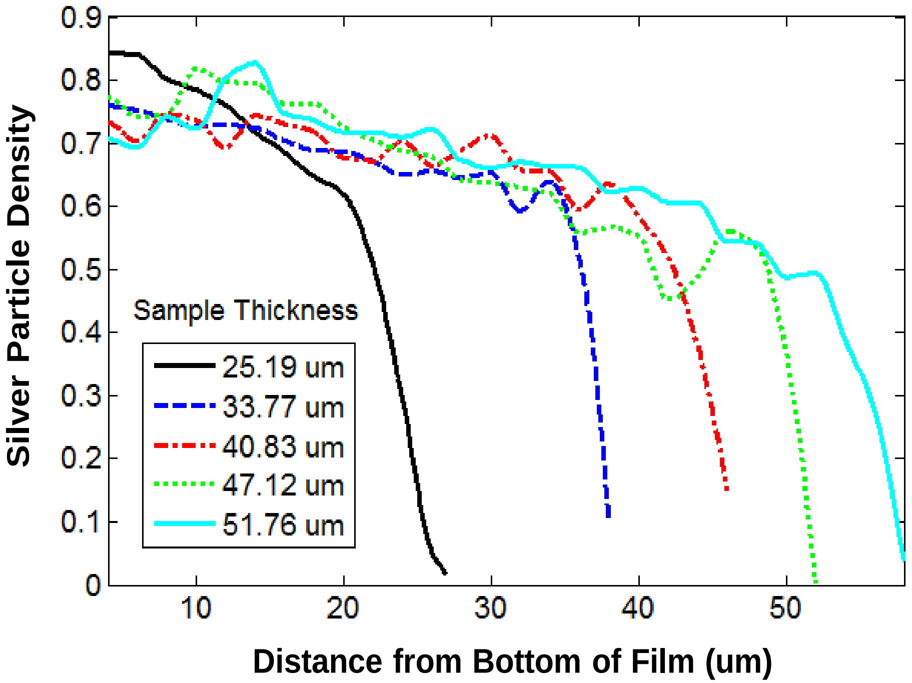
Losses & Frequency Limits

Surface roughness

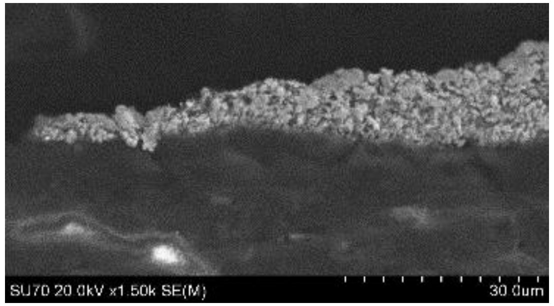


Non-uniformity

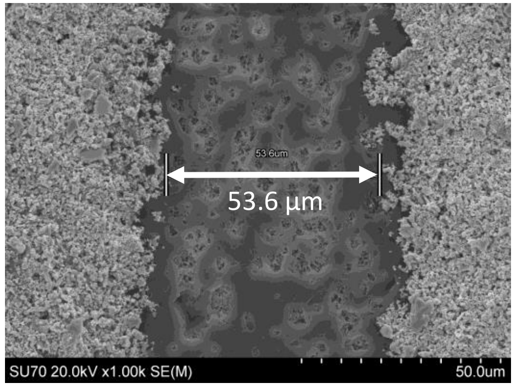




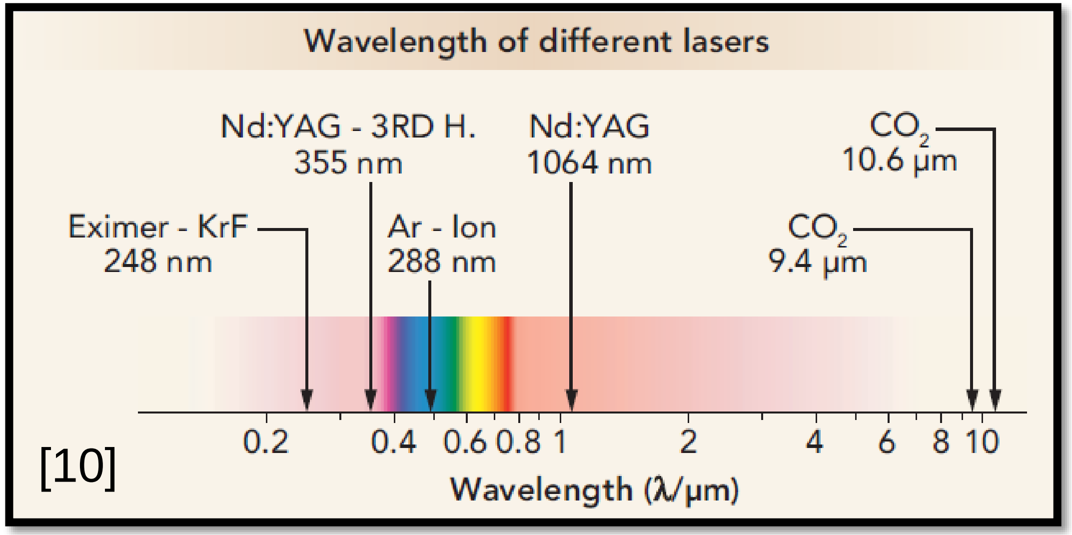
Tapered edges



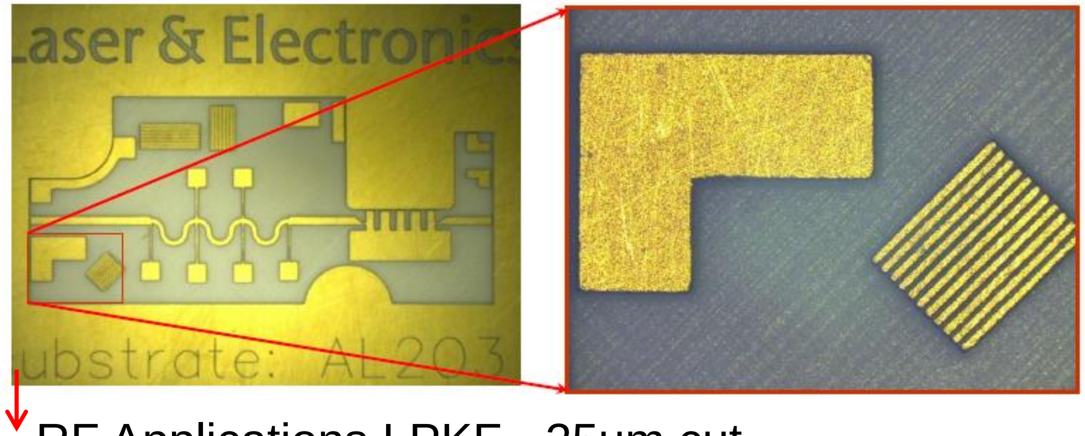
Maximum resolution of 50 μm



Laser Enhanced DDM



[10]



RF Applications LPKF - 25um cut

CO2 (top) vs Nd: YAG (bottom) cut on Kapton

CO2

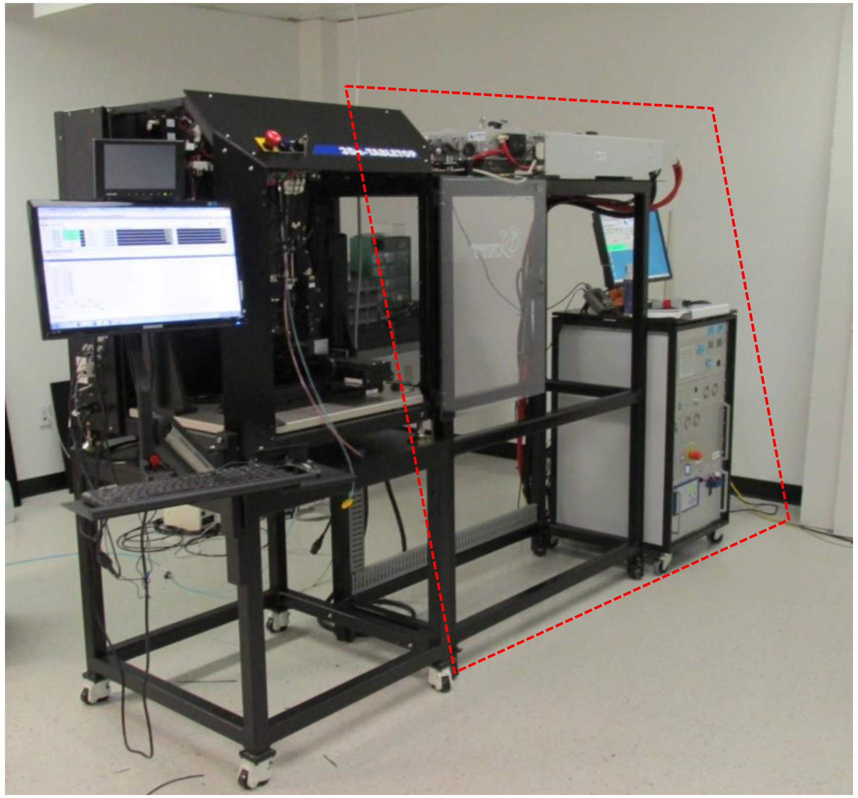
- λ : 10.6 um
- Pulse width: ms to ns
- Local Heating, melting, material vaporization
- Thermal damage

Nd : Yag

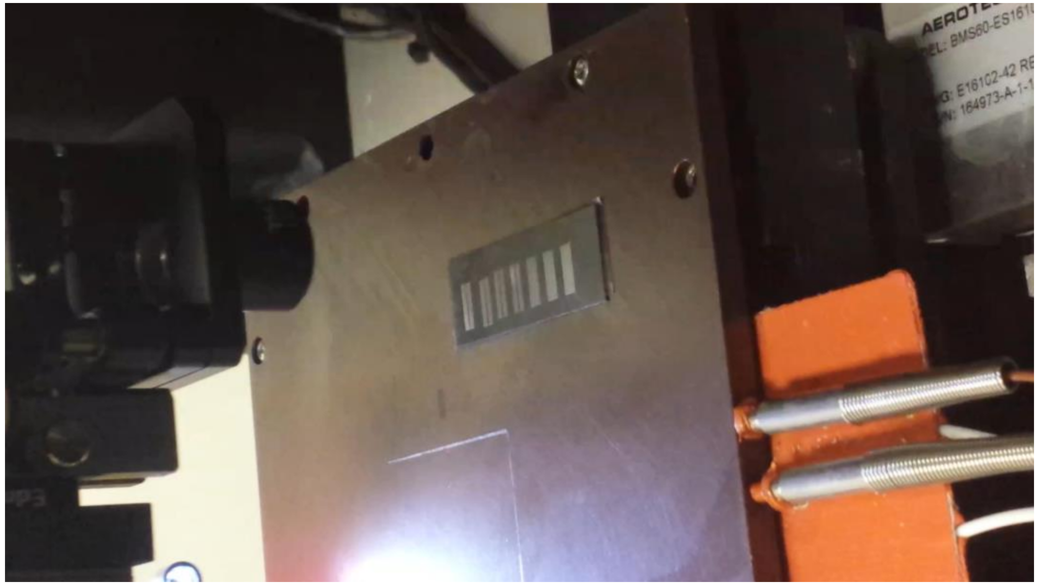
- λ : 1064 nm
- Pulse width: ps, fs
- Cold ablation
- Greatly reduced thermal damage

Laser Enhanced DDM

Picosecond Laser Machining
Lumera Nd:YAG



Video:



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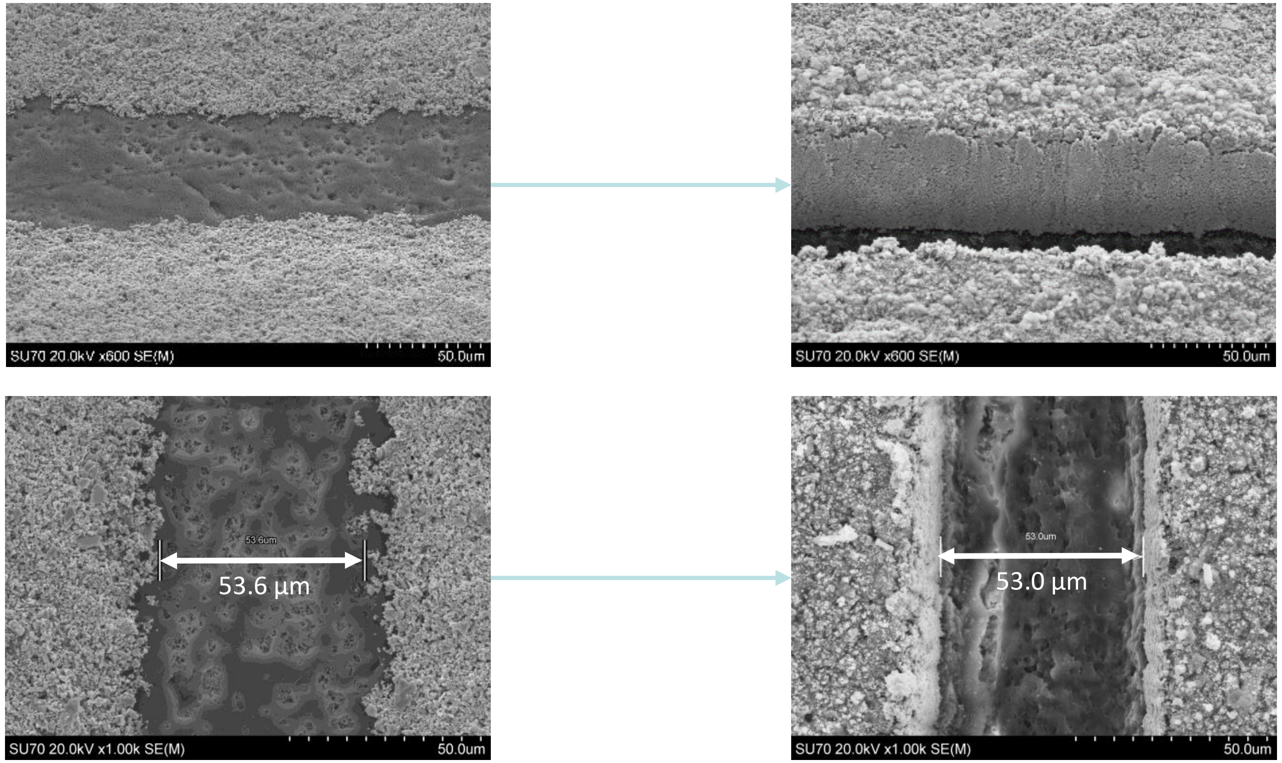
Laser Enhanced DDM

Micro-Dispensing | Micro-Dispensing + Laser Machining

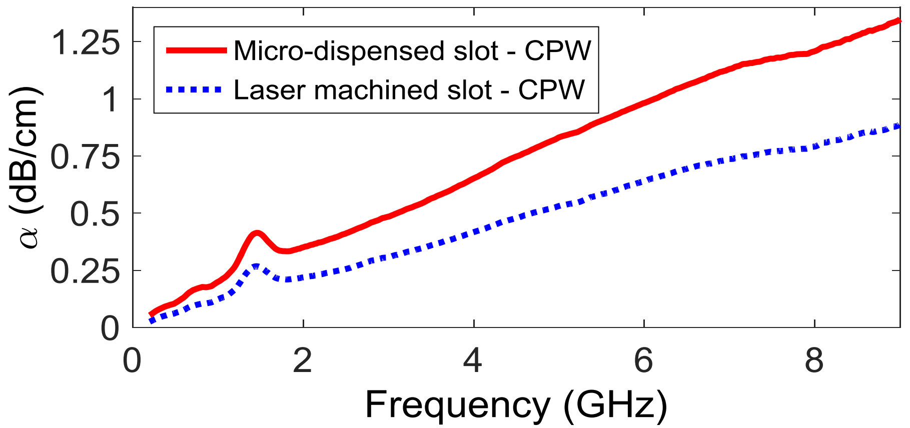


Pulsed ps Nd:YAG laser

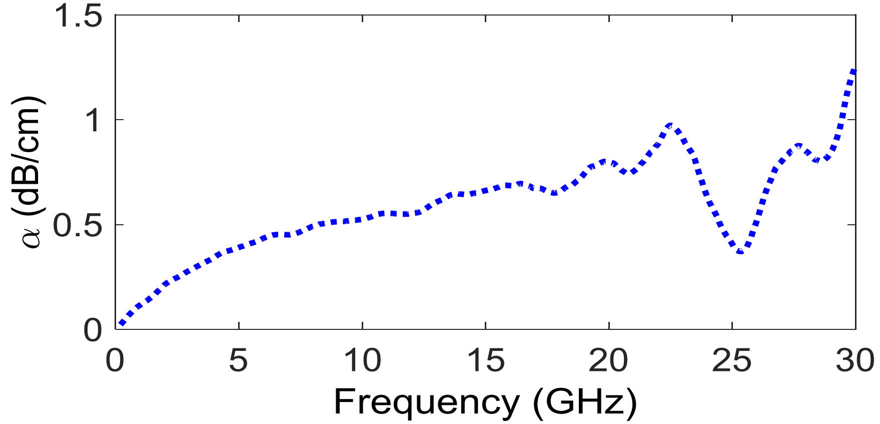
E. A. Rojas-Nastrucci, Harvey Tsang, Paul Deffenabugh, T. M. Weller, Ramiro A. Ramirez, D. Hawatmeh, and Kenneth Church, “Characterization and Modeling of K-Band Coplanar Waveguide Digitally Manufactured using Pulsed Picosecond Laser Machining of Thick-Film Conductive Paste,” in IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 9, pp. 3180-3187, Sept. 2017.

Laser Enhanced DDM

Loss of CPW with slot size of 50 μm



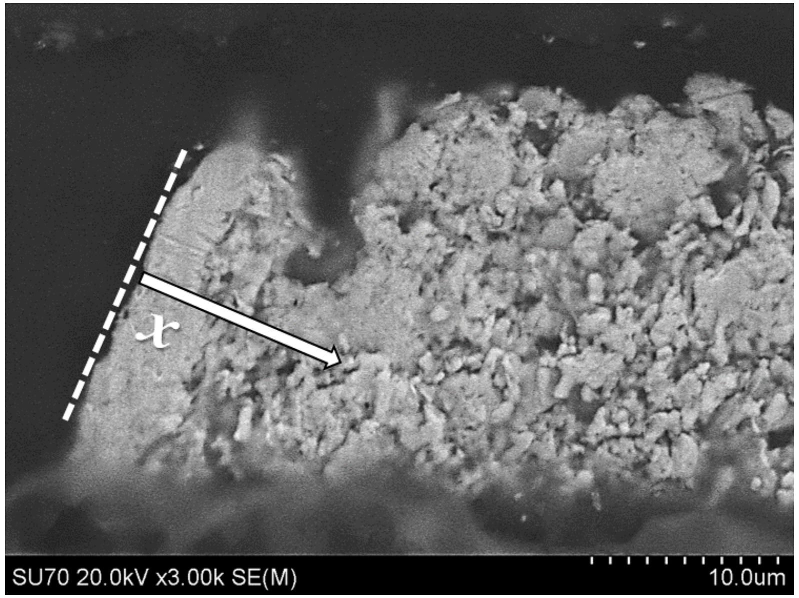
Loss of CPW with slot size of 20 μm

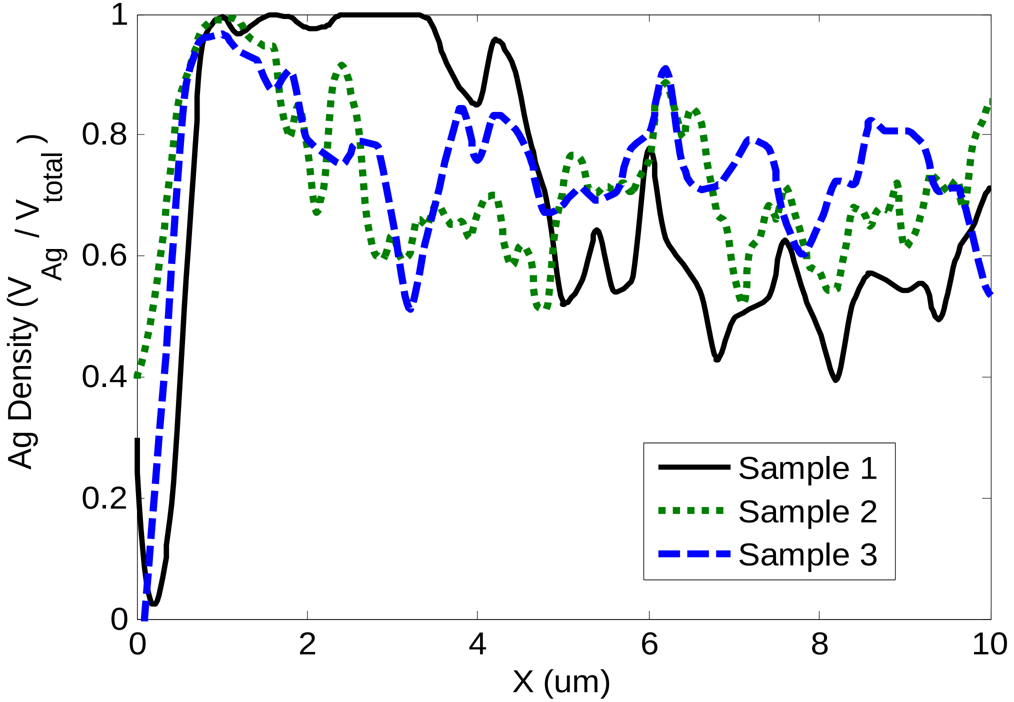


Micro-dispensed CB028: σ_{eff} < 1e6 S/m
Laser machined CB028: σ_{eff} > 1e7 S/m
Attenuation comparable to Cu cladding

E. A. Rojas-Nastrucci, Harvey Tsang, Paul Deffenabugh, T. M. Weller, Ramiro A. Ramirez, D. Hawatmeh, and Kenneth Church, "Characterization and Modeling of K-Band Coplanar Waveguide Digitally Manufactured using Pulsed Picosecond Laser Machining of Thick-Film Conductive Paste," in IEEE Transactions on Microwave Theory and Techniques, vol. 65, no. 9, pp. 3180-3187, Sept. 2017.

Laser Enhanced DDM





Near-solid silver in ~2 micron-wide region

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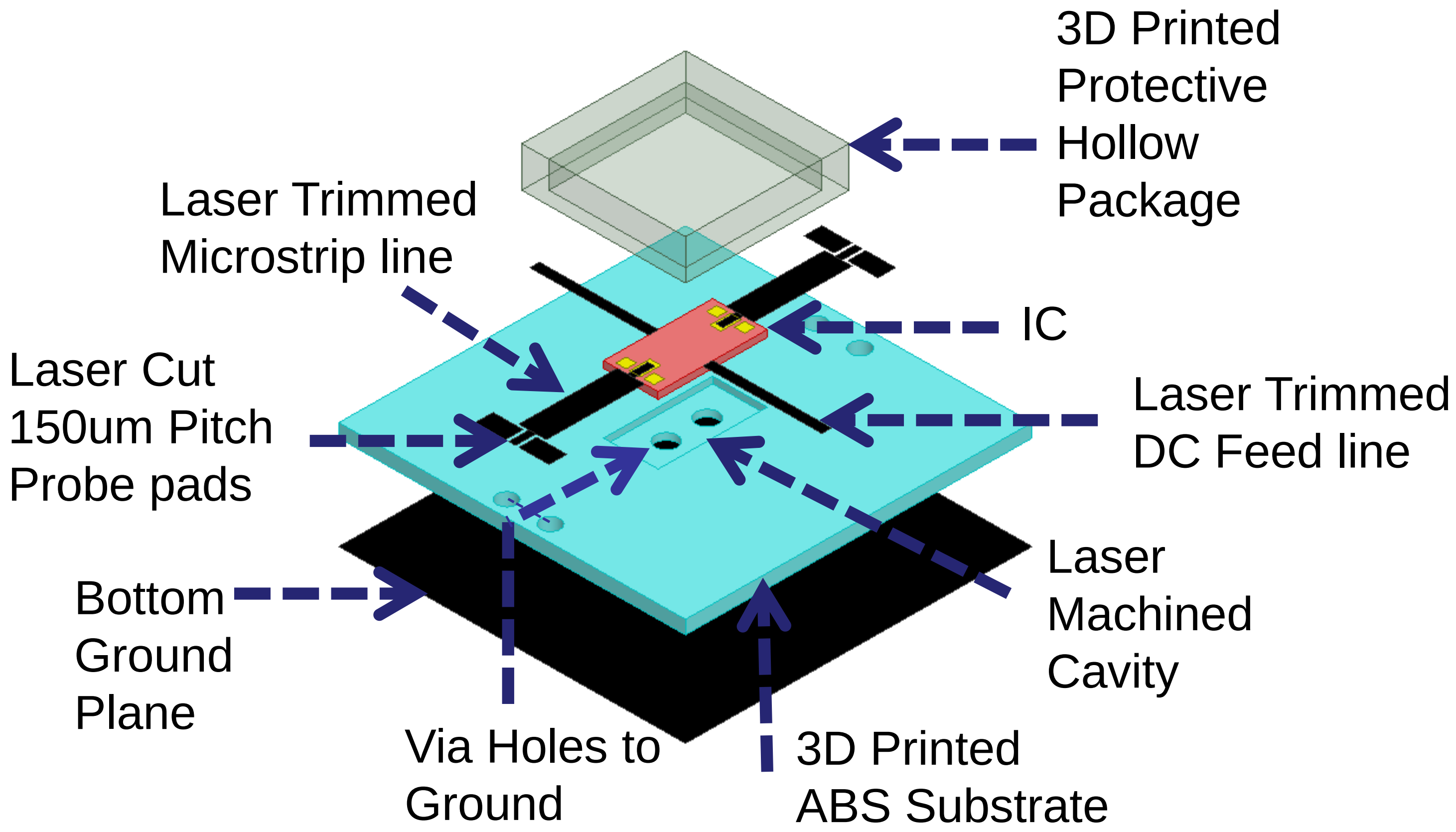
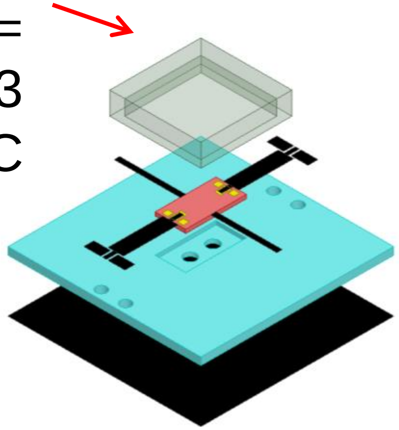
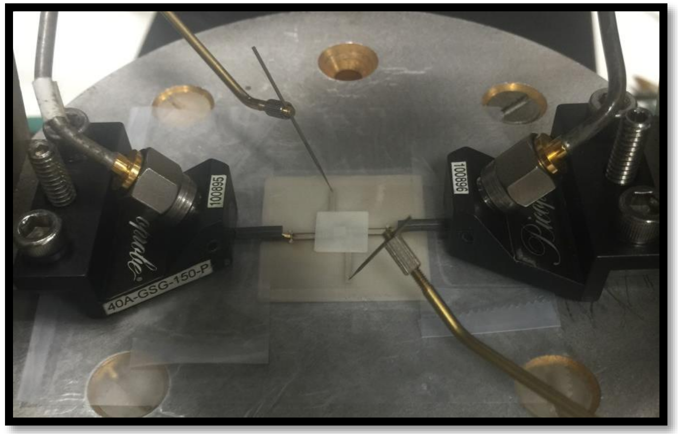
DDM 3D Packaging Concept

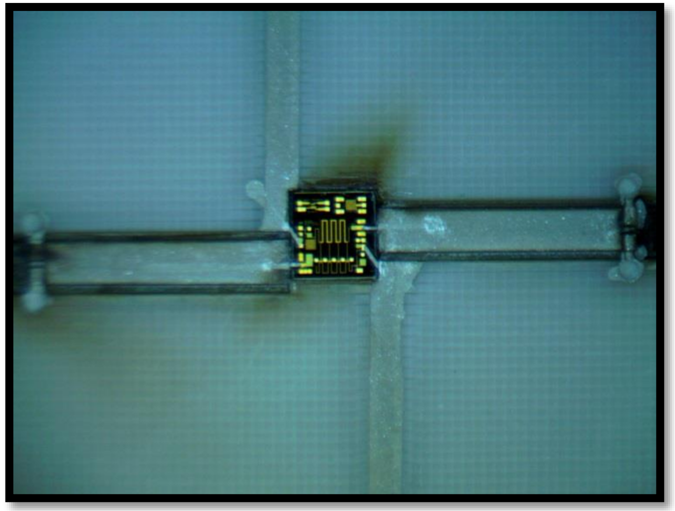


Fabricated Package

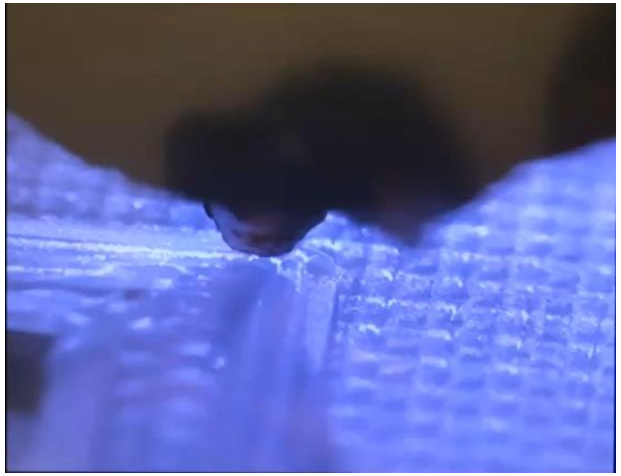
3D Printed Hollow cover
Dimensions =
6 x 6 x 0.3 mm^3
100 um clearance from IC







Video:



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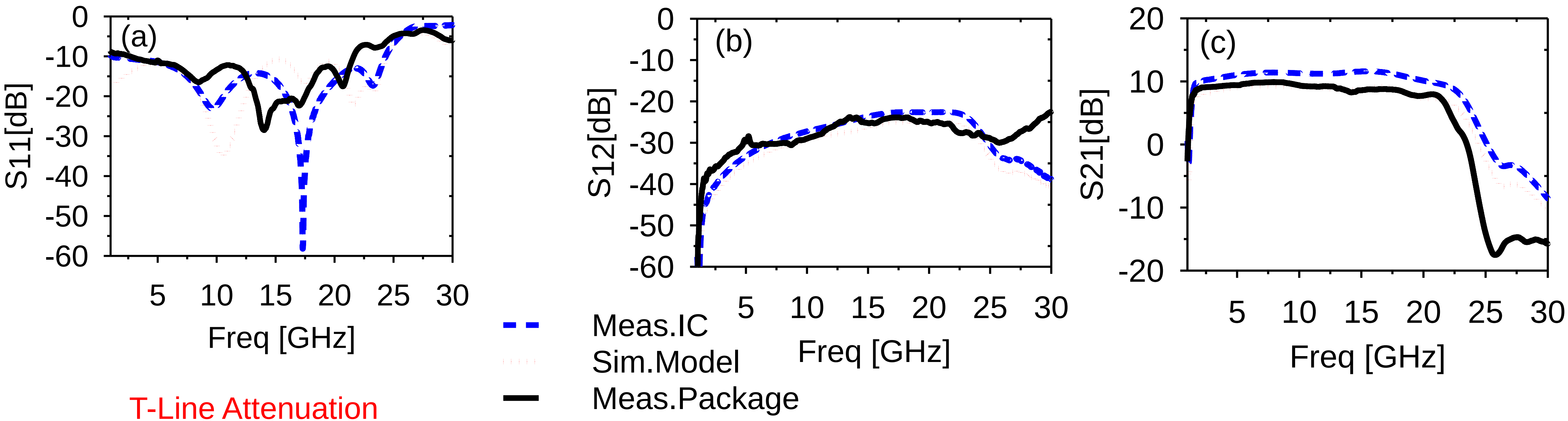
Simulated & Measured Data



T-Line Attenuation

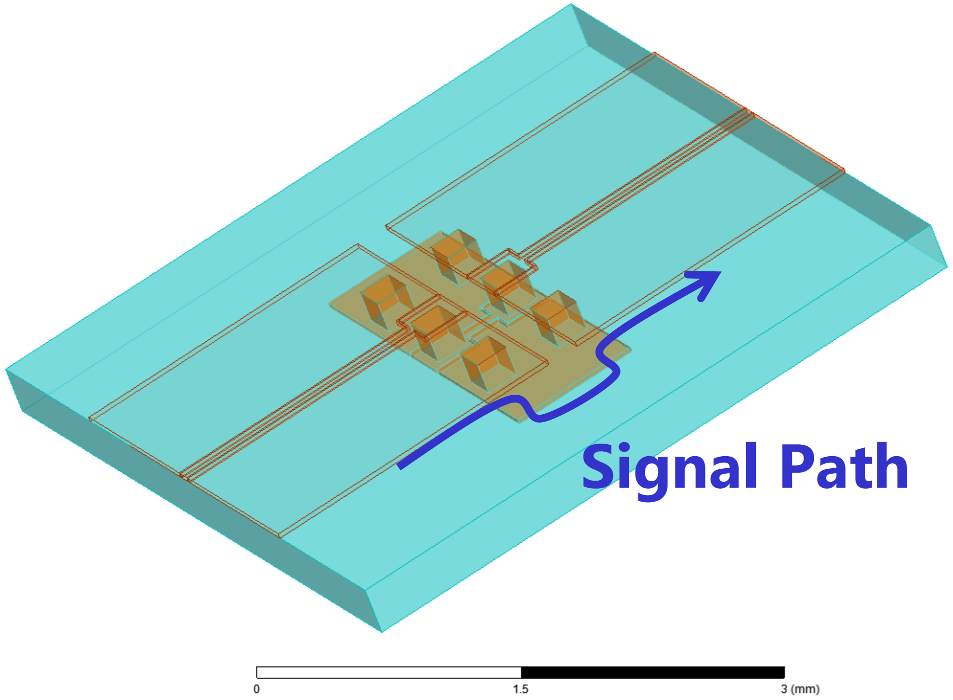
5 GHz – 0.125 dB/mm

20 GHz – 0.2 dB/mm

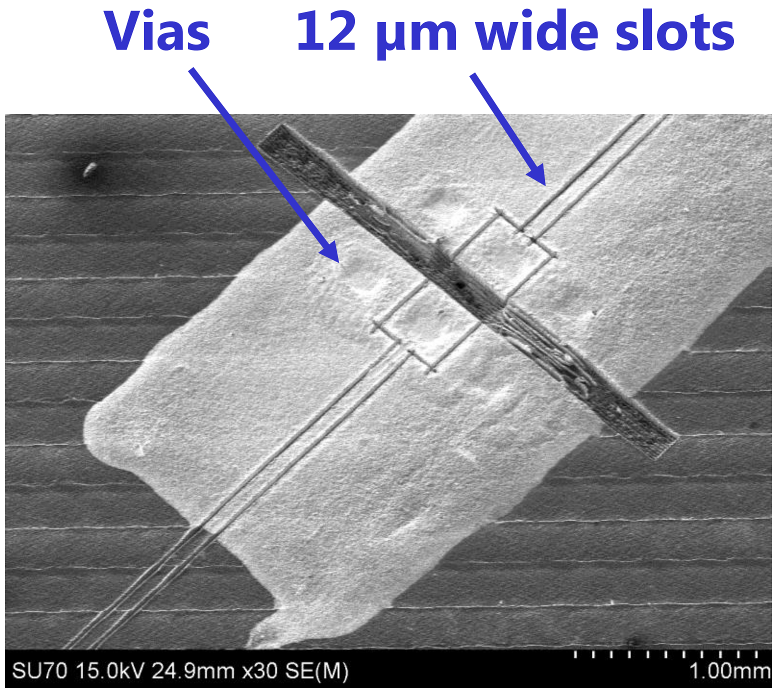
Return loss

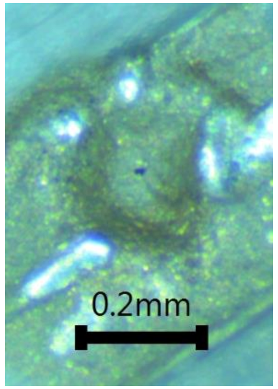
10 dB – within frequency band of interest

DDM Multi-Layer Interconnects



Simulated Structure

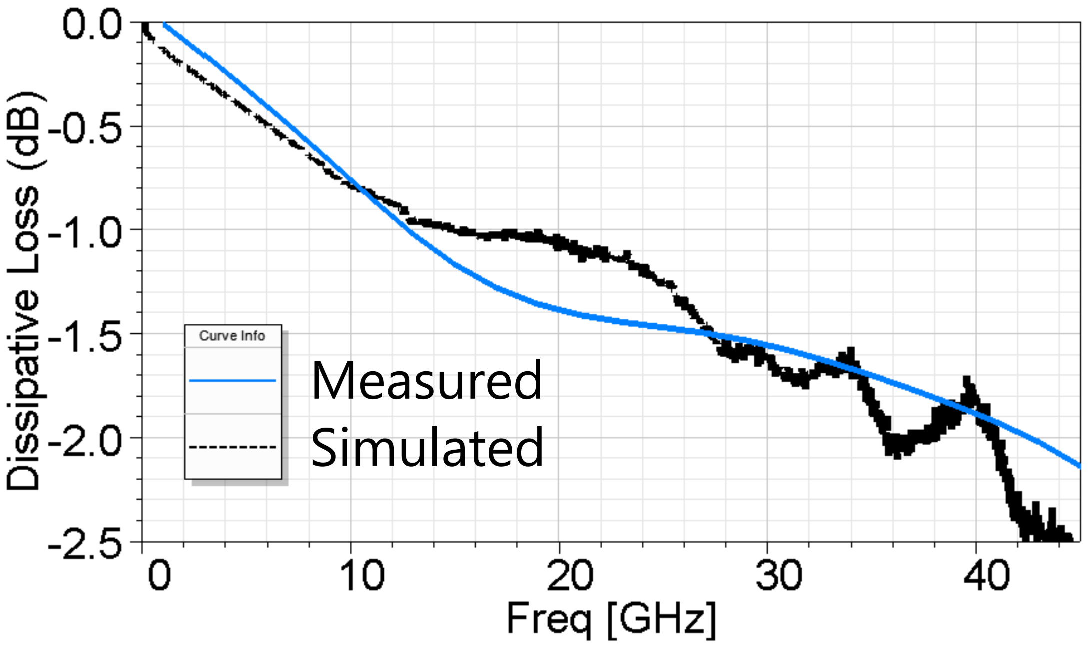


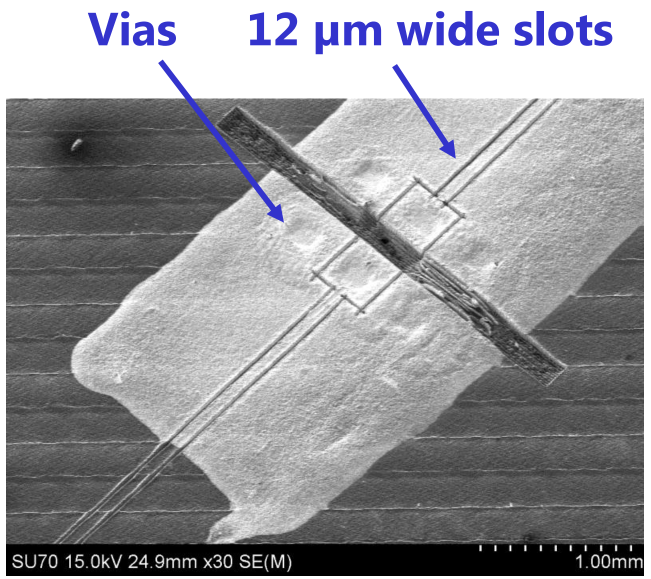


Fabricated Structure

- Dielectric layers are ABS with a thickness of 50 µm.
- CB028 micro-dispensed with a typical layer thickness of 25 µm
- Traces are machined using picosecond laser, achieving 12 µm wide slots.

DDM Multi-Layer Interconnects





Fabricated Structure

- Test structure that includes two CPW vertical transitions shows 4.25 dB/cm of loss at 40 GHz.

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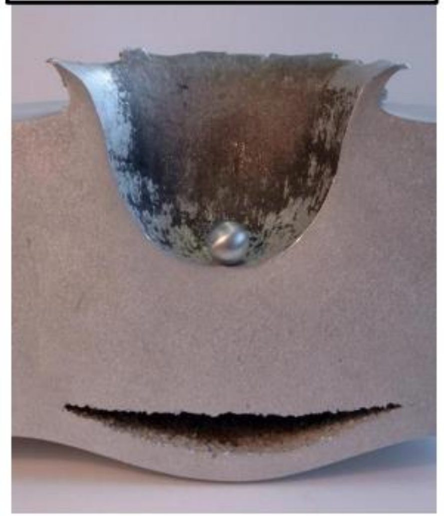
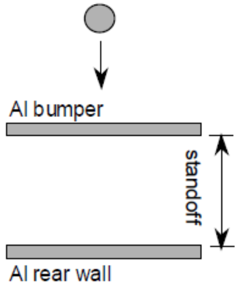
Novel Sensing Mechanisms

Structures for Micro Meteorite Orbital Debris (MMOD) Impacts

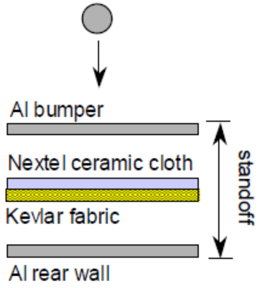
- MMOD impact velocities can reach 15 km/s for space debris and 70 km/s for meteoroids.
- Space debris in earth orbit – more then 166 million 1mm-1cm particles
- To protect space structures from MMOD impacts, the outer skin is generally consisted of multiple protection layers.
- Inflatable structures have multiple soft-goods layers comprised of bladder, restraint, and MMOD layer made of fiberglass/Kevlar cloth and low density foam.

Comparison of size of projectile to size of impact crater

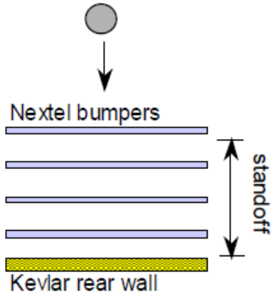




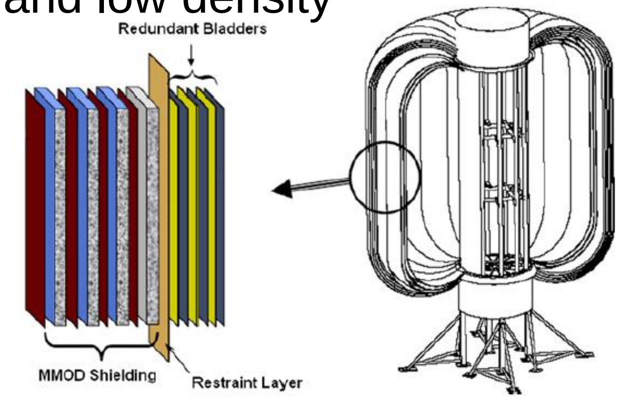
Whipple Shield[1]



Nextel/Kevlar Whipple[1]



Flexible Multi-shock[1]



Cross-sectional schematic[2]

1. Christiansen, E. L. "Meteoroid/Debris Shielding," NASA Johnson Space Center, Houston, Texas, TP−2003-210788, 2003.
2. E. J. Brandon, M. Vozoff, E. A. Kolawa, G. F. Studor, et al., "Structural health management technologies for inflatable/deployable structures: Integrating sensing and self-healing," *Acta Astronautica,* vol. 68, 2011, pp. 883-903.

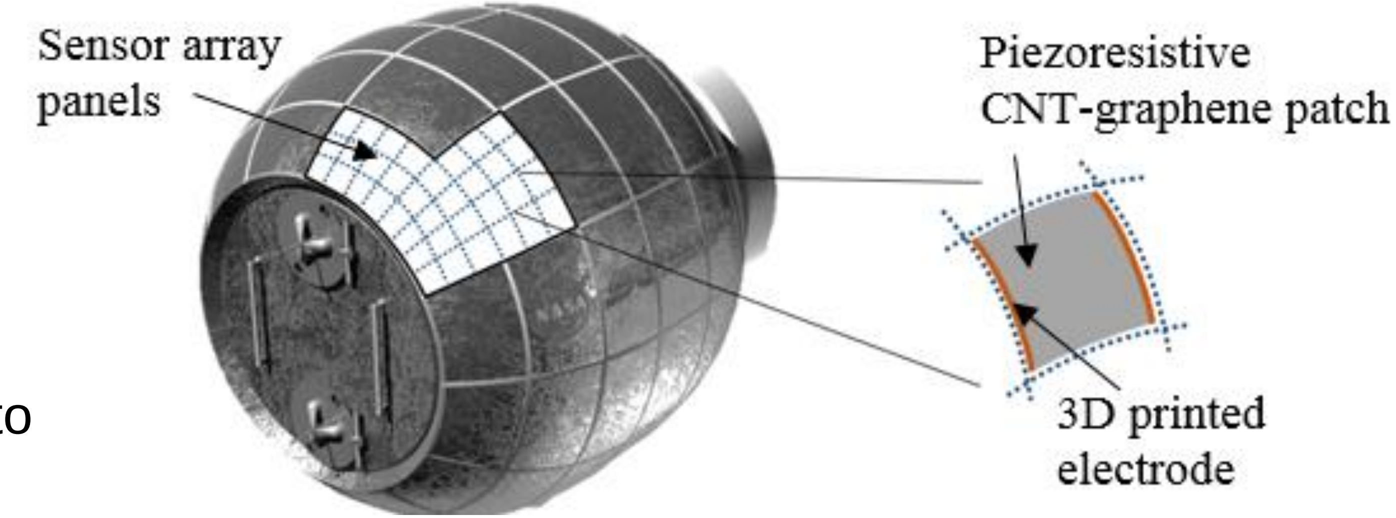
Novel Sensing Mechanisms

- **Objective**

Develop an MMOD impact detection system that can be incorporated into the inflatable structure. An integrated SHM system should provide existence and location of damage, depth of penetration, and damage extent.

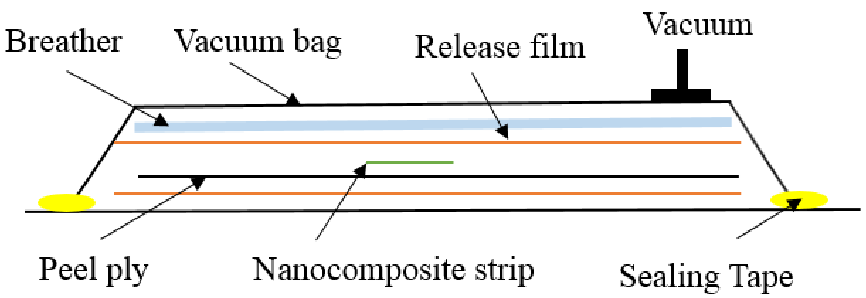
- **Approach**

  - Develop flexible piezoresistive sensors composed of carbon nanotubes sheet and coarse graphene platelets.
  - Perform static and dynamic impact testing to measure sensor performance.
  - Perform multi-sensors and multi-layers impact testing to prove MMOD detection capabilities.

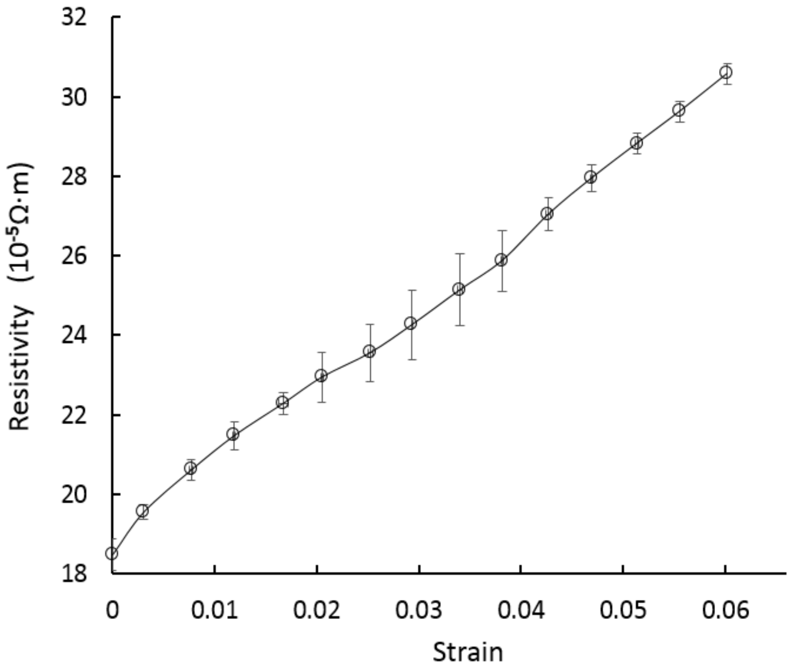


Materials

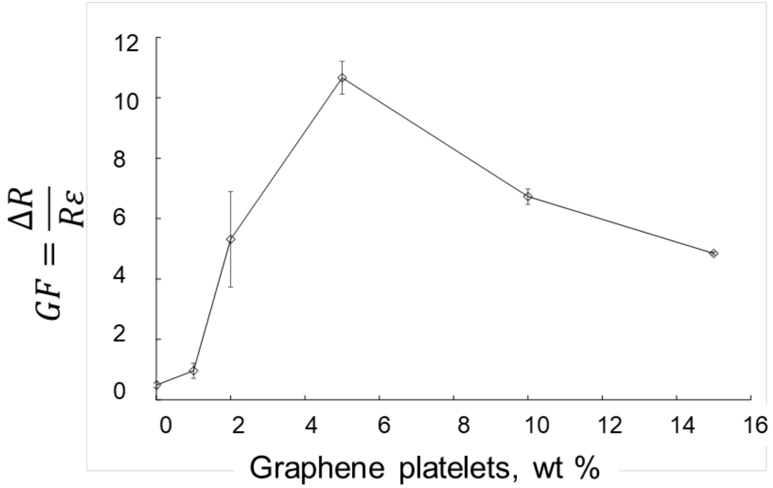
- Buckypaper base with copper end tabs
- 105 epoxy resin and 206 hardener
- Additives: coarse graphene platelets (5 wt%)
- Fabricated by vacuum bagging



Gage factor (GF) by graphene contents



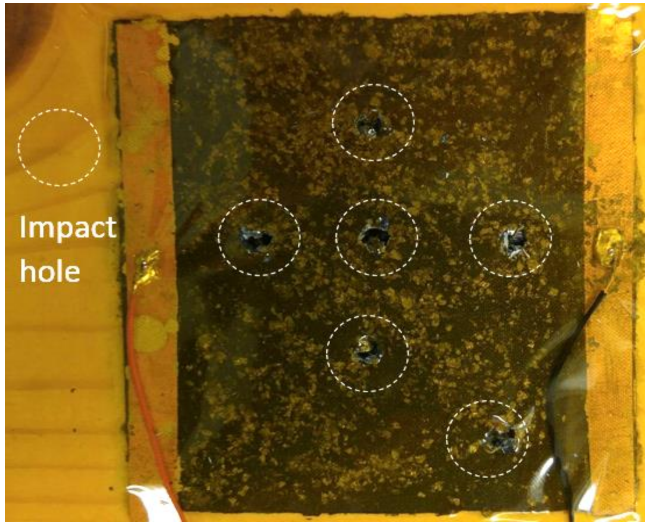
- Strain vs resistivity

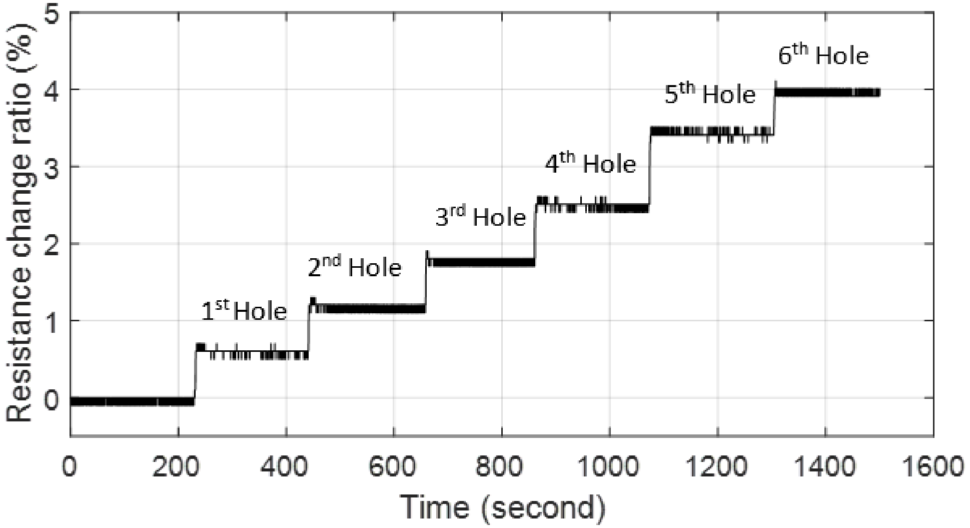


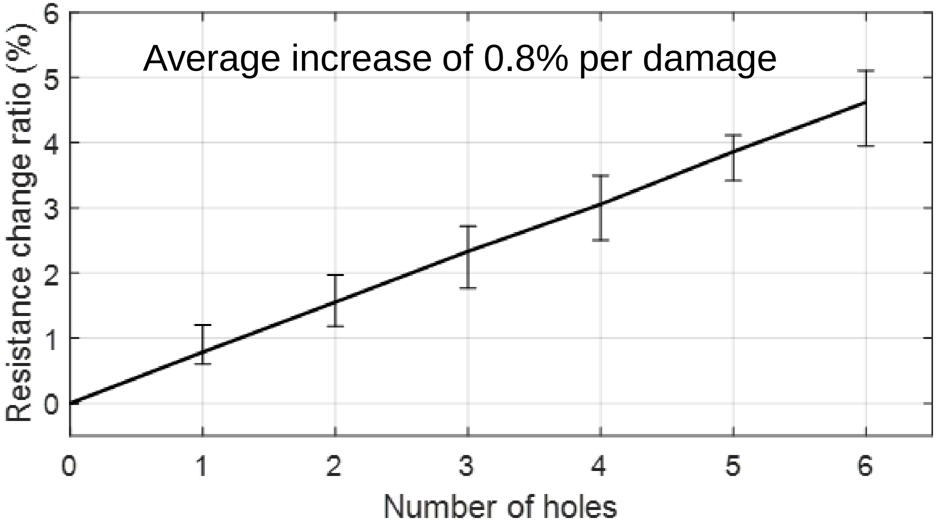
- Gauge factor increases from 0.49 to 10.66 from 0 to 5 wt% GP.

Static Puncture Testing

- Resistivity with multiple holes
  - 2.5 in x 2.5 in nanocomposites covered with Kapton tape; six holes are successively added.
  - Change in resistance when subject to static damage induced by drilling 3 mm holes.
  - Resistance remains constant with added holes → stable

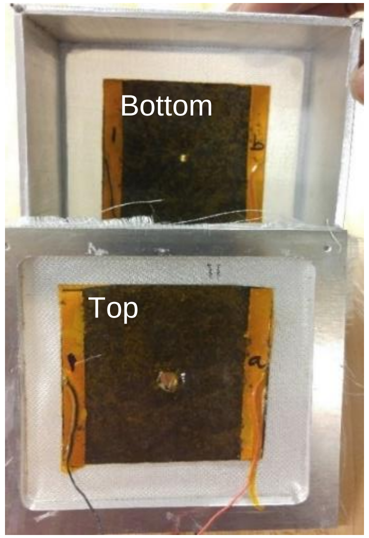


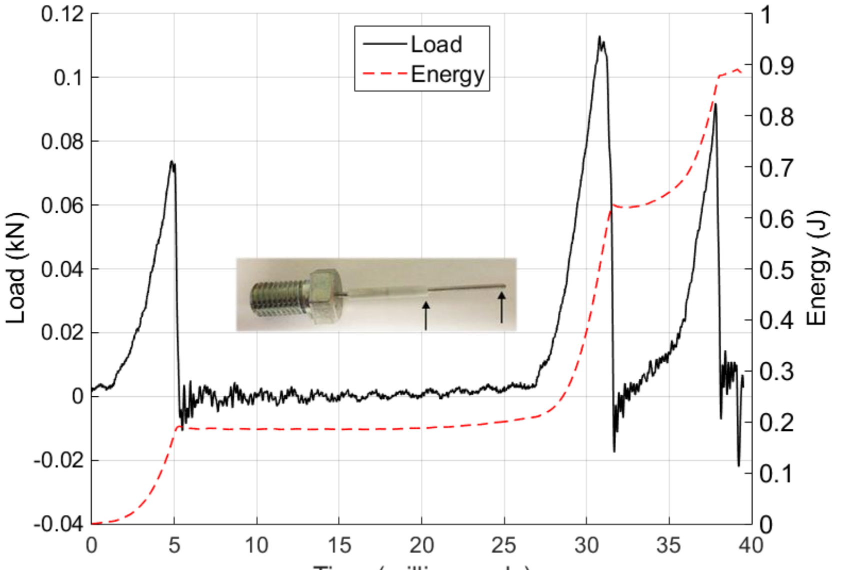


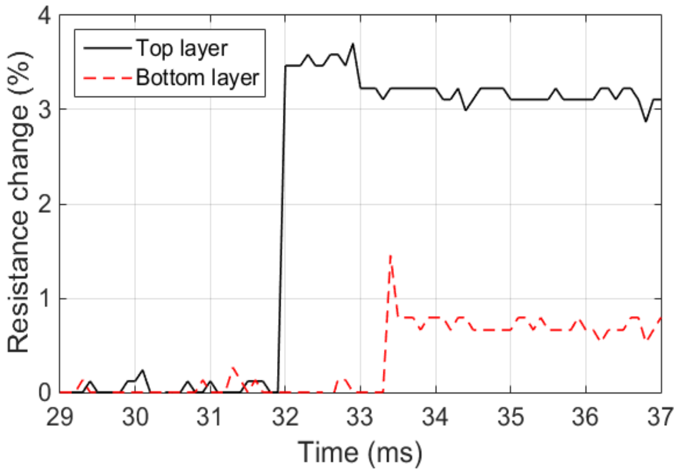


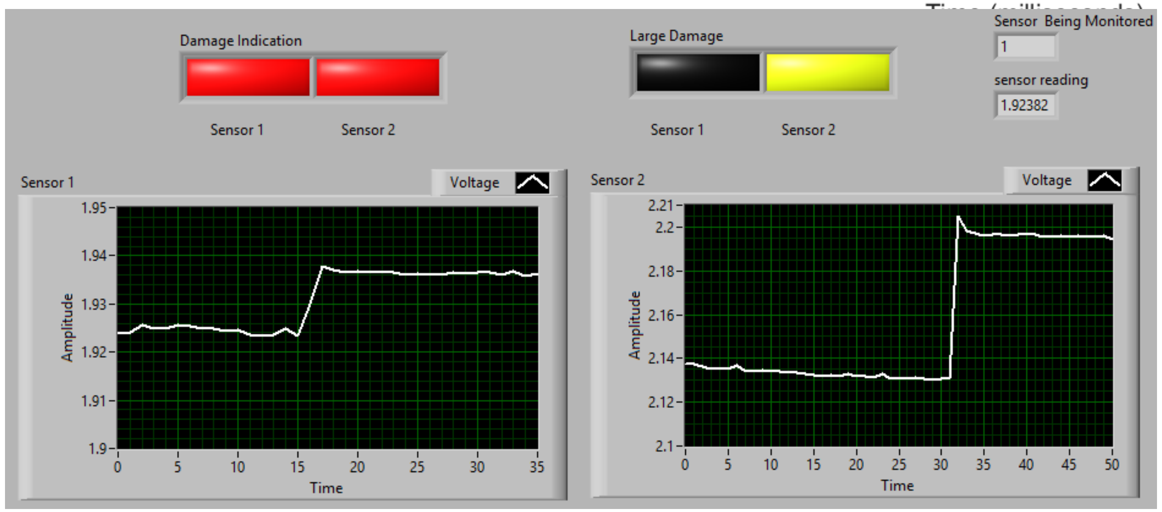
Low velocity Impact Results

- Single impact with different hole sizes
  - Load and energy: the 1st, 2nd, and 3rd peaks represent the tip on top layer, larger diameter on top layer, and tip on the bottom layer, respectively.
  - LabVIEW for double layer impact: larger change resistance change on top than bottom due to the size of indenter.









layer

*Note: time is not synchronized in this VI

Aerospace Innovation Complex

60 Airplanes for students, 4 for faculty, only in the Daytona Beach Campus

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Aerospace Innovation Complex

- **Embry-Riddle Research Park**
- Opening first building (engineering lab & incubator space) imminently
- 4000+ sqft ECSSE labs, including Radar/20GHz, circuit mill/assembly, anechoic chamber; 8000 sqft roof lab.
- State of the art additive manufacturing capabilities.
- Access to RF measurement (probing station) up to 110 GHz.
- Second building (Wind Tunnel) under construction

Aerospace Innovation Complex

- Space environment plasma chamber
- Environmental chambers for instrument and payload calibration upto 6U CubeSats
- 1 m3 Thermal Vacuum chamber for flight qualification
- *Solar simulator for end to end CubeSat power system testing.
- Air bearing table and 3-axis Helmholtz coil for attitude determination and control testing
- Vibration and shock table
- Class 10,000 clean room
- Anechoic chamber for EMC and comm testing

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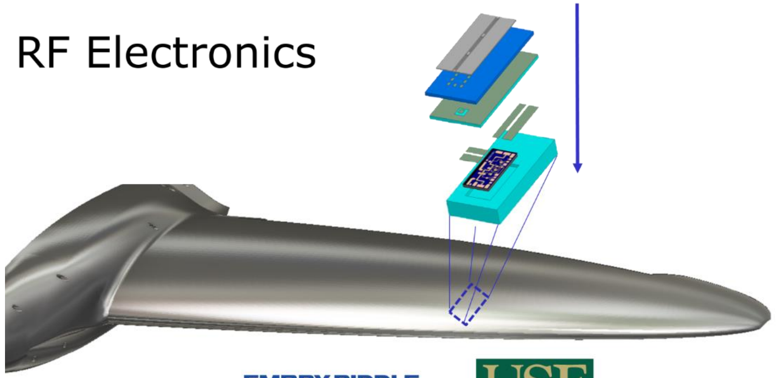
WiDE Lab – Wireless Devices and Electromagnetics Laboratory

Research related to Wireless Systems for Aerospace Applications:

WiDE LAB

Structural Monolithic

RF Electronics



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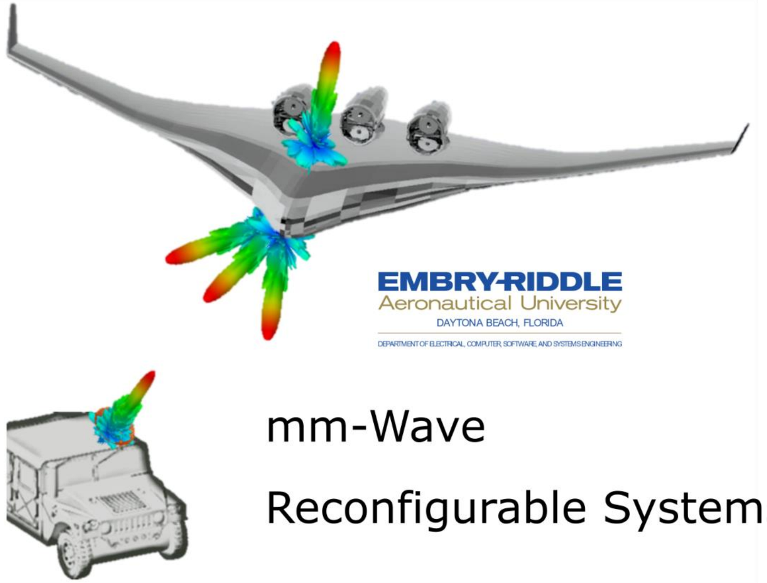

mm-Wave

Reconfigurable Systems

www.wide-lab.com

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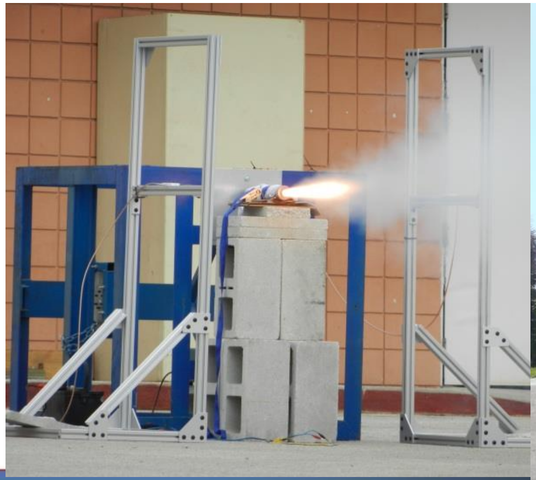
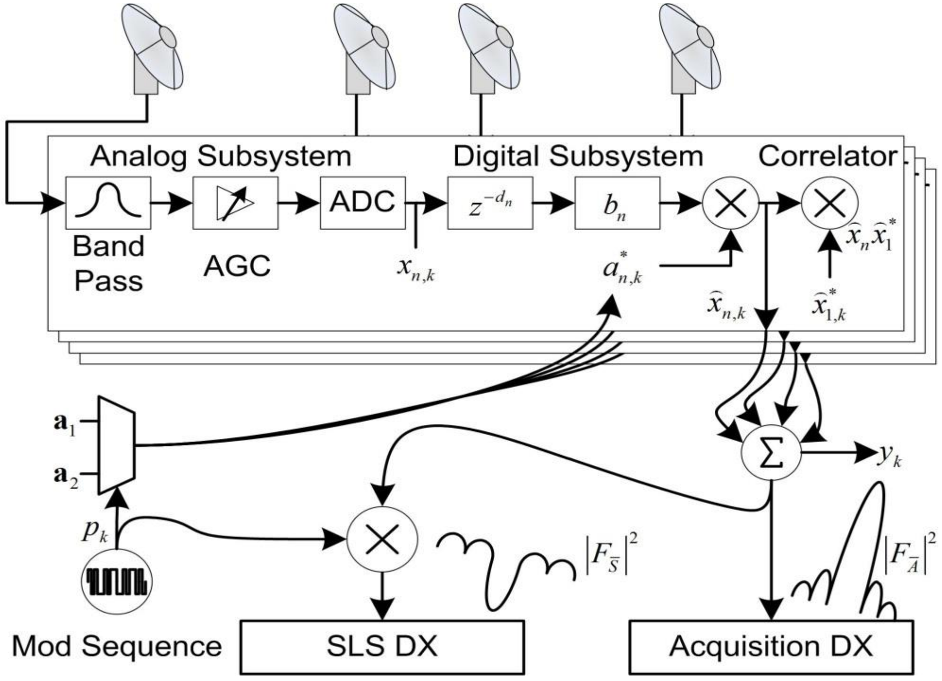
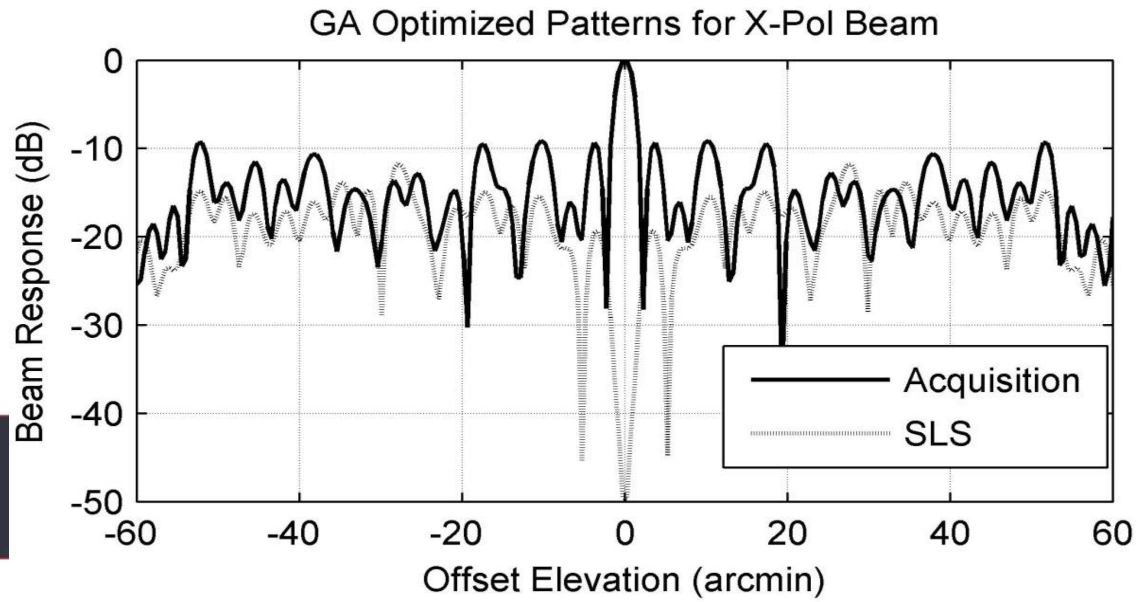
ERAU Radar & Microwaves Lab

- Design systems & techniques for exploiting weak RF signals for physical measurements

- Main work: Passive radar, radio astronomy, SETI, phased/timed antenna arrays, telemetry/com







TMA

- Approach: Time Modulated Arrays
- Old idea, new application (radio astronomy)
- Apply beam switching inside real-time beamformer to code-multiplex “target” and “sidelobe suppression” beams – zero-cost enhancement to existing system
- Because of limited sensitivity, not well-fit for forming secondary science beams; “only” good for RFI excision (great application!)

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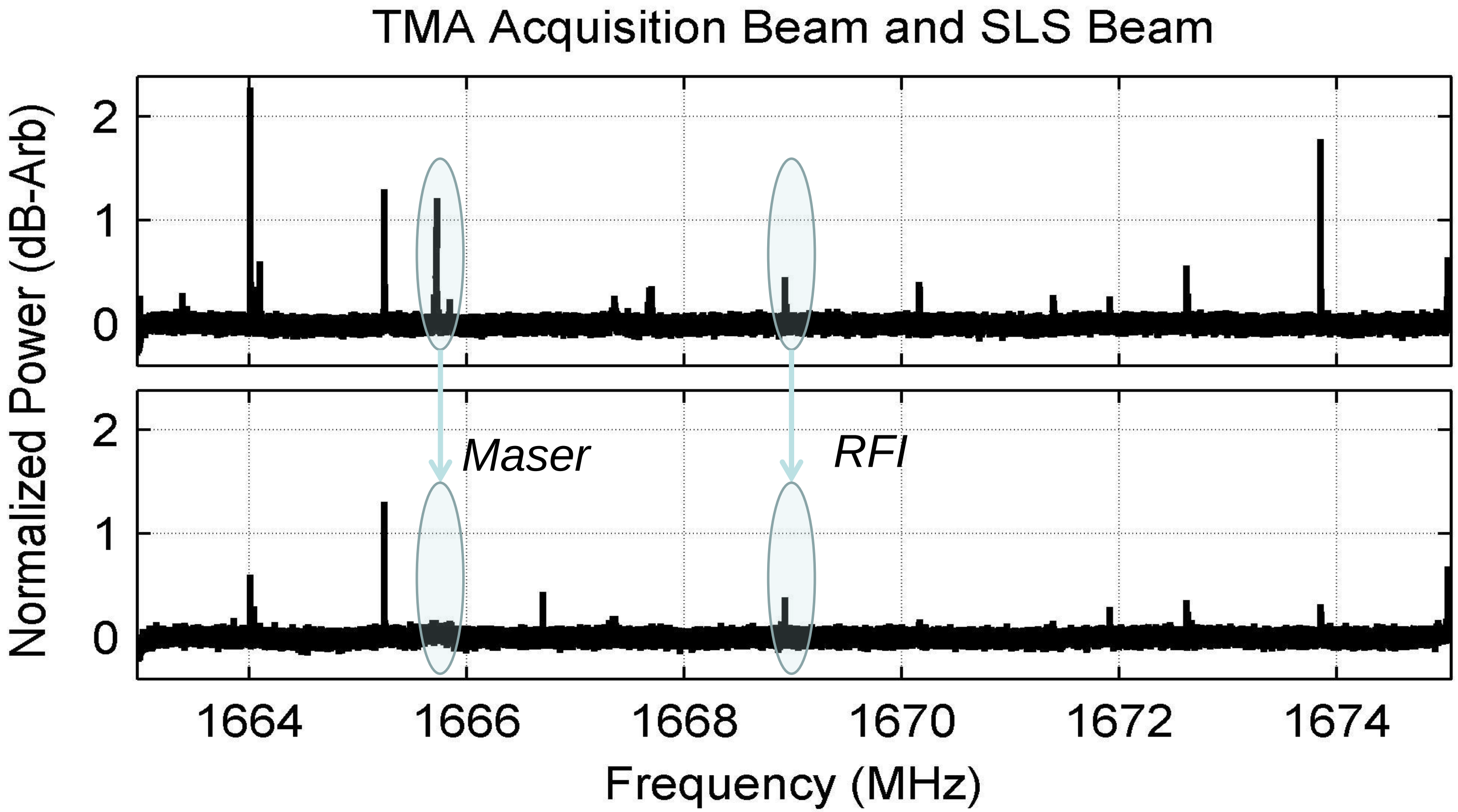
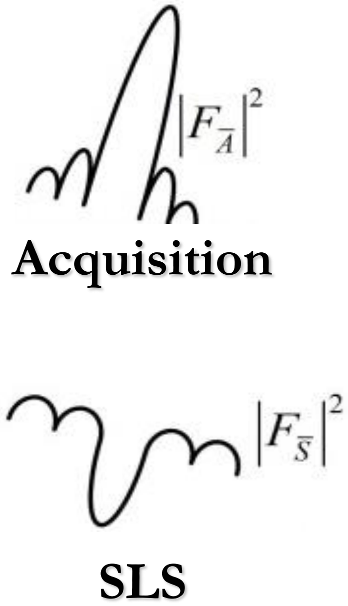
TMA Result: Discriminated RFI



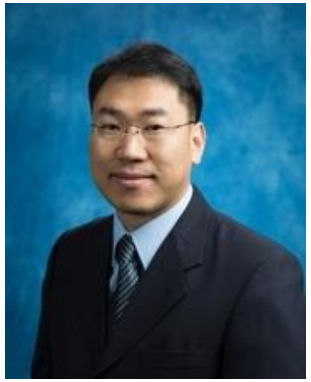


240 kHz modulation during beamforming, GA, X-pol (51.2 Hz RBW)
Process with 5σ signal detector & use SLS for exclusion

Dr. Eduardo A. Rojas-Nastrucci
ECSSE Department
ERAU

Dr. Thomas Weller
EE Department
USF

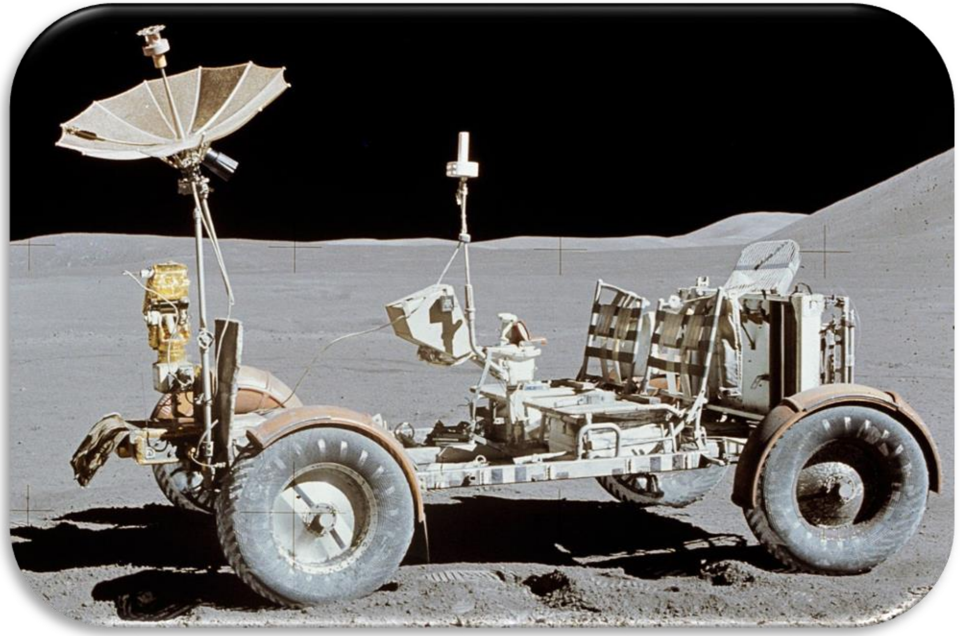
Dr. William Barott
ECSSE Department
ERAU



Dr. Daewon Kim
AE Department
ERAU

Dr. Sirish Namilae
AE Department
ERAU

Thank you



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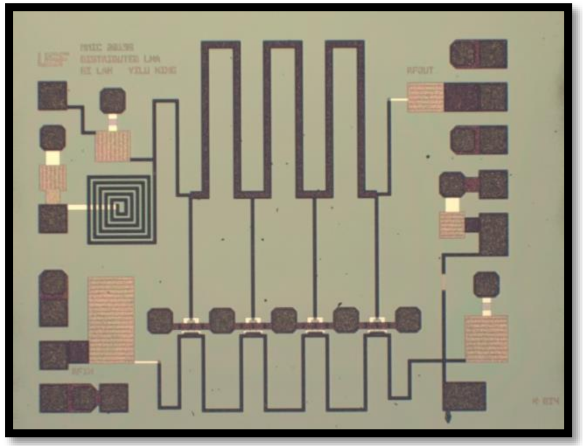
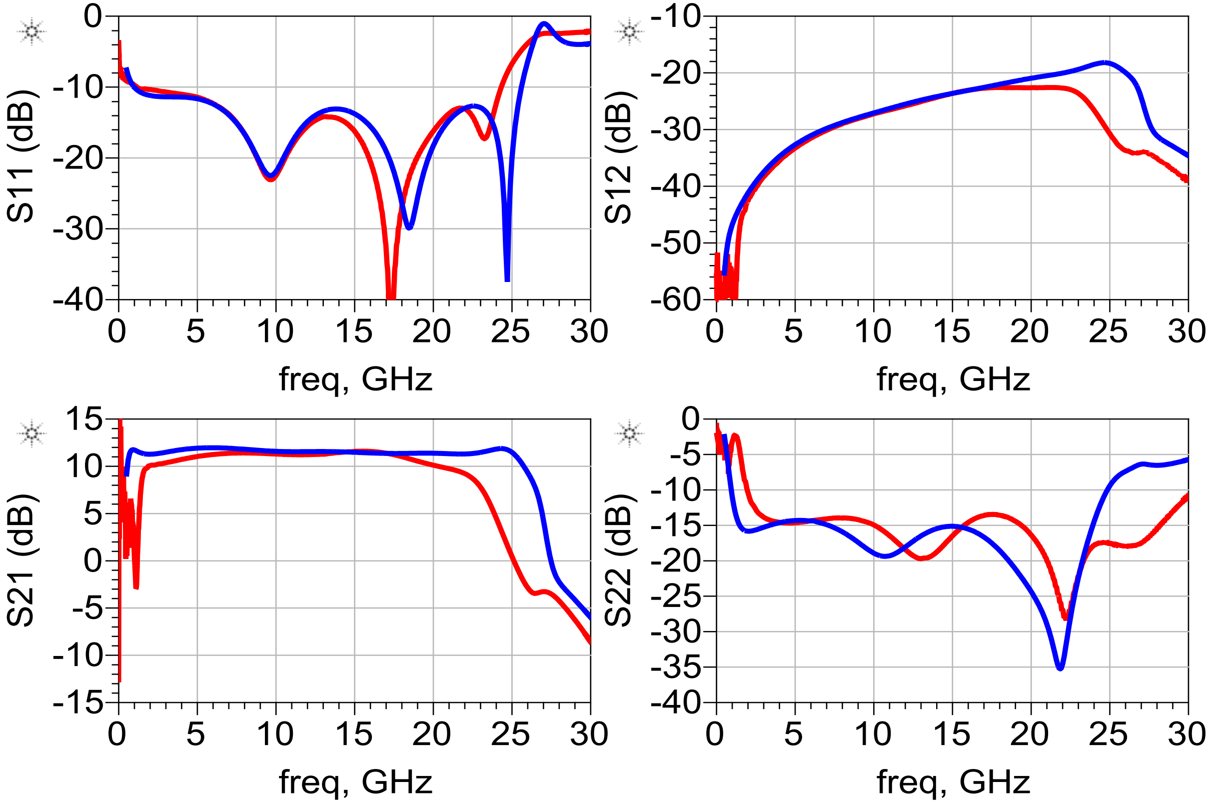
GaAs MMIC Distributed Amplifier



- TQPED 0.5µm
  GaAs pHEMT
- Size: 1.8mm x 1.5mm
- Frequency: 2~22GHz
- 11 dB with ±0.5 dB ripple
- 1.8 VSWR input/output

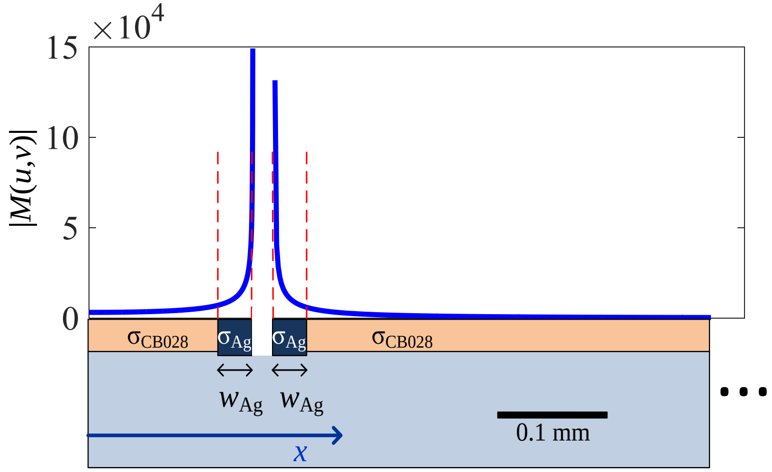


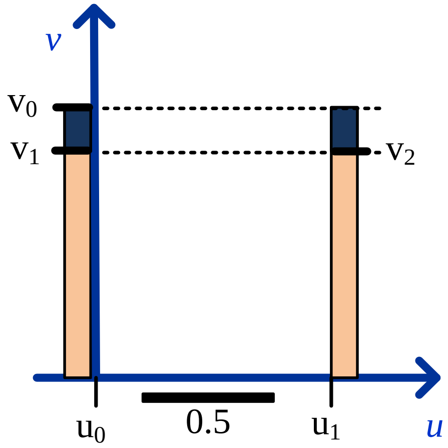
Measured Data

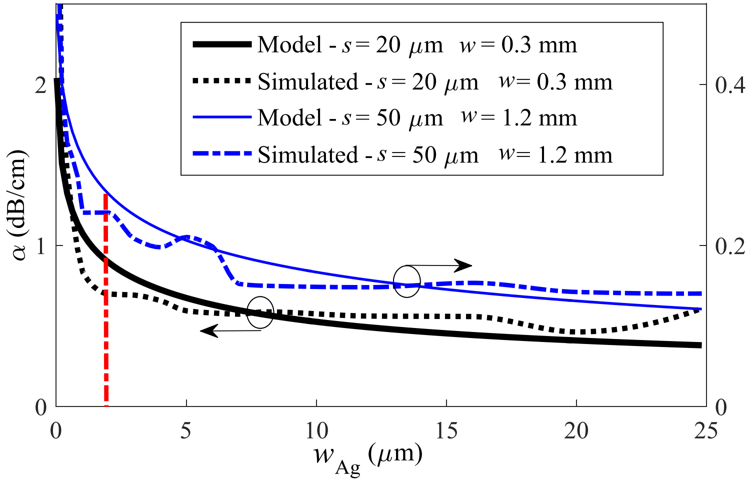
ADS Simulation V_{dd}=4V, I_d=93.8mA

Laser Enhanced DDM

Modeling of the picosecond laser machining effects:







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