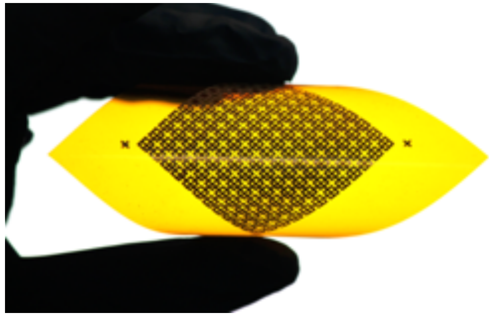
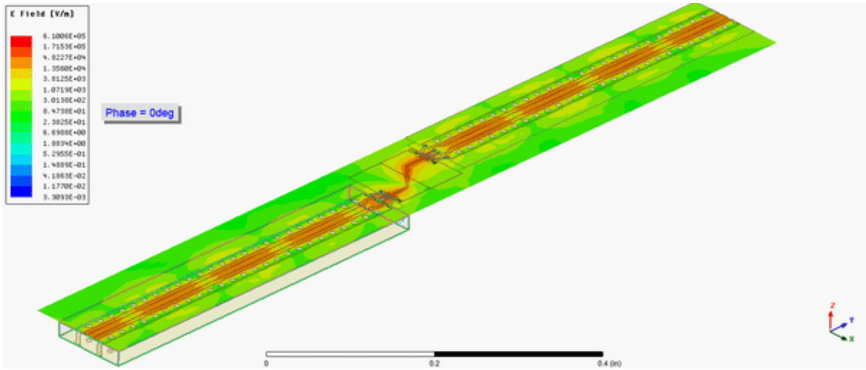
Printed Electronics and Additive Microelectronic Packaging For RF/Microwave Applications





Prof. Craig Armiento

University of Massachusetts Lowell

Raytheon UMass Lowell Research Institute (RURI)

Printed Electronics Research Collaborative (PERC)

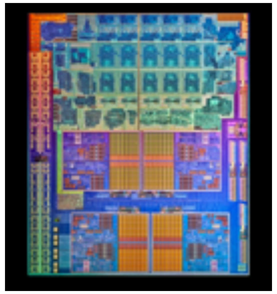
iMAPS Northeast Workshop, May, 2, 2017

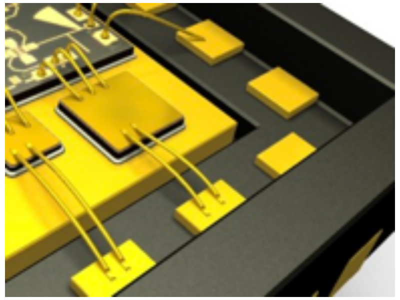
Outline

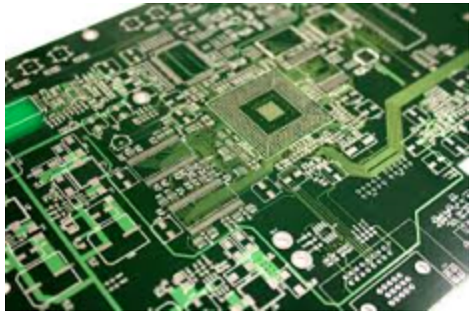
- **Challenges for Printed Electronics for RF/Microwave Applications**
- **Printed Electronics Research through Corporate-Academic Partnerships**
  - Raytheon-UMass Lowell Research Institute (RURI)
  - Printed Electronics Research Collaborative (PERC)
- **University of Massachusetts Lowell - Facility and Capabilities**
- **Sample Projects**
  - Printed Frequency Selective Surfaces (FSS)
  - Ferroelectric ink and printed varactors/phase shifters
  - Additive microelectronic packaging
  - 3D antenna arrays
  - Printed connectors
- **Closing Thoughts**

Printed Electronics and Microelectronic Packaging

- Printed Electronics technology works in the dimensional regime between the submicron geometries of ICs and the much larger dimensions of PCBs… which is the scale needed for microelectronic packaging





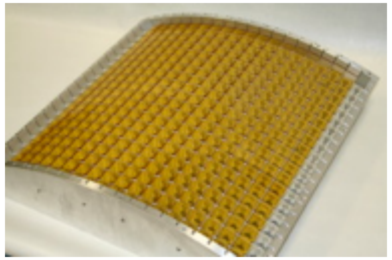


Feature sizes ICs < 1 micron packaging: 10's of microns PCBs: 100's of microns

- The performance requirements of RF/microwave systems require best of breed semiconductor active ICs
  - Printed RF transistors are not ready for prime time due to the low mobility of printed semiconductors
- Microwave modules require a variety of different functionalities and require the integration of many different circuit elements, interconnects and connectors

Applications for Printed RF/Microwave Electronics

- **Defense Applications**
  - Low cost, flexible radar systems

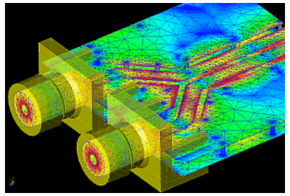


- **Anything that's wireless** (with an Antenna)
  - IoT

- **5G Cell Phones**
  - 30 GHz, 64 element antenna arrays

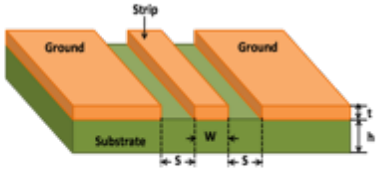
- **Medical Devices**
  - Smart drug delivery systems

PE Challenges in RF/Microwave Applications



Complex Circuit/Module Design
Electromagnetic simulation rather than conventional lumped element modeling

Integration of Active Electronics
Need to integrate high performance ICs and printed CPW interconnects



Coplanar Waveguide (CPW)

High Frequency Interconnects
Need controlled impedance interconnects, reduce parasitics. Surface roughness matters

Substrate and Ink Development
Plastic films not developed for electronics properties. Surface finish, dielectric properties need to be controlled

Material Characterization
Dielectric properties needed at high frequencies. Mechanical, thermal properties of printed materials and inks

Thermal Management
New substrate materials will challenge thermal management – particularly in high power applications

Connectors
If the goal is to change the form factor (e.g., flexible) why use standard connectors?


Printed metasurface antenna with SMA connector

Tunability
Reconfigurable components to maximize performance such as phased-array antennas

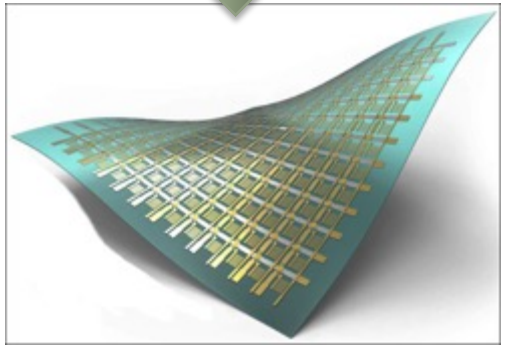
RURI/PERC Initiative: What & Why

- **Research Focus: Printed Electronics (PE) & Additive Manufacturing(AM)**
  - Focus on wireless and RF/microwave applications
  - Materials, processes, devices, characterization, integrated modeling
  - 2D and 3D, flexible, conformable form factors
  - Initial focus on DoD applications but expanding to commercial applications
- **Design, fabricate and characterize materials and prototype devices quickly**
  - Accelerates product design, designers can take more risk
- **Corporate partnerships on sponsored research projects related to AM/PE**
- **Develop the supply chain for Printed Electronics**
- **Pursue corporate, state and federal and funding opportunities**
- **Leverage university infrastructure and expertise**
  - Plastics engineering, nanomanufacturing
- **Talent Acquisition**
  - Train the next generation of engineers in AM and PE

PE Research Through Corporate/Academic Partnerships

- **Raytheon-UMass Lowell Research Institute (RURI)**
  - New co-location model for university-industry collaboration
  - Raytheon employees have offices, work with UML faculty, students
  - Projects supported from internal R&D funds
  - Significant partnerships in federal funding
- **Printed Electronics Research Collaborative (PERC)**
  - PERC has raised over $6.7M in corporate and federal funds
  - Preposition teams for federal funding opportunities
  - 13 companies have joined PERC …more coming

Raytheon, BAE SYSTEMS, SI2, tsi, FLEXcon, ROGERS CORPORATION, MICRO CHEM, BARRY, CREATIVE MATERIALS (Creating Conductive Solutions), OSRAM, Anokiwave (mmW Solutions. Enabling a new world), OPTOMEC, TTM Technologies (Time-To-Market Interconnect Solutions), HASELMEIER (Drug Delivery. Tailormade.)

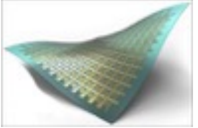


Changing the form factor and reducing cost for radar systems

Bringing the Supply Chain Together to Speed Innovation and Adoption

Developing the Printed Electronics Supply Chain

Systems



Flexible Phased Array Radar

Subsystems

- Phased Array Antennas
- AM-Based Printed Circuit Boards
- Frequency Selective Surfaces

Components

- Thin ICs with Printed Interconnects
- Printed Transistors
- Antennas
- Metamaterial Based Devices

Processing Equipment

- 3D structural printers
- Functional ink printers-2D
- Functional ink printers for 3D objects
- Pick & Place die mounting on flex substrates
- Optical & thermal sintering

Modeling & Design for AM

- Modeling Tool Integration; Structural, EMag, thermal…
- EMag Design & simulation
- Software for 2D to 3D circuit layout
- Materials modeling & engineering

Printable Materials

- Electrically Conductive Inks
- CNTs & graphene
- Flexible low loss Substrates
- Dielectrics
- Ferroelectric materials
- Thermally Conductive Inks

PERC/RURI has been visited by over 90 companies and organizations

Rapid Prototyping Using Printed Electronics

RURI/PERC has capabilities for all parts of the development cycle

Design and Simulation

↓

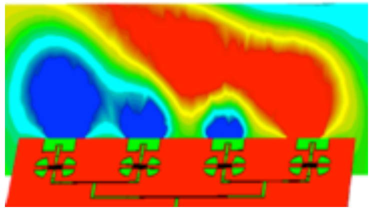
Material Development

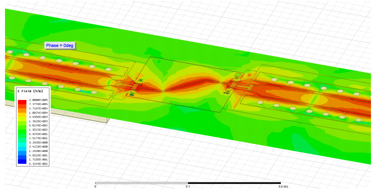
↓

2D/3D Printing & Processes

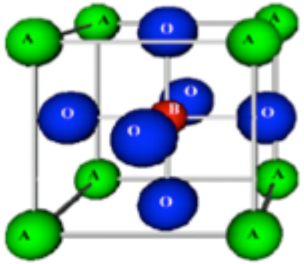
↓

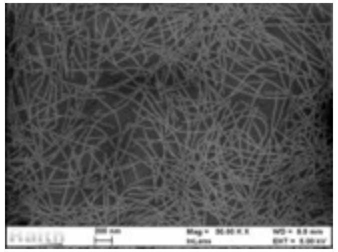
RF/Microwave Characterization

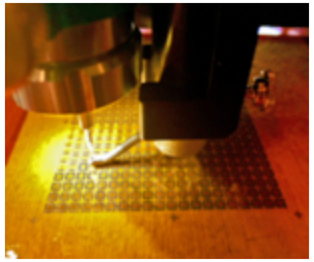


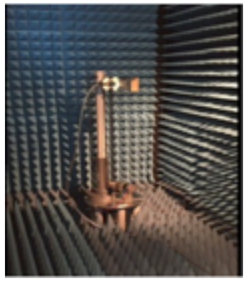


BST





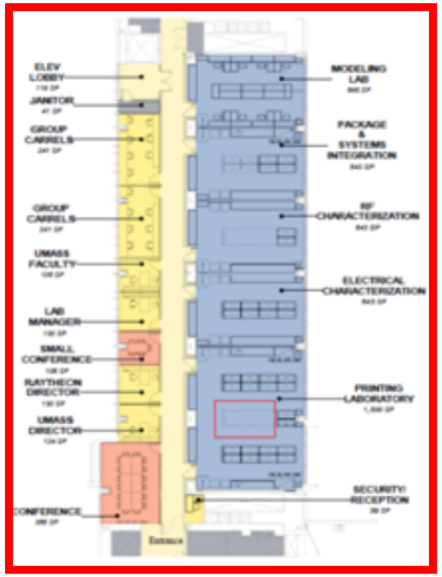




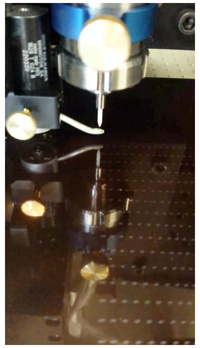
Design iterations for additive processes measured in days not months

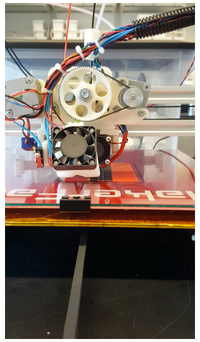
Extensive Printed Electronics Capabilities

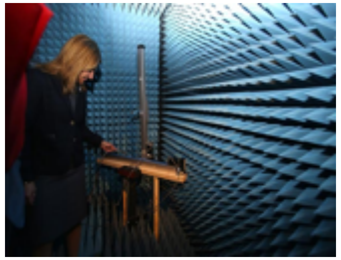
4th Floor Saab Emerging Technologies Building

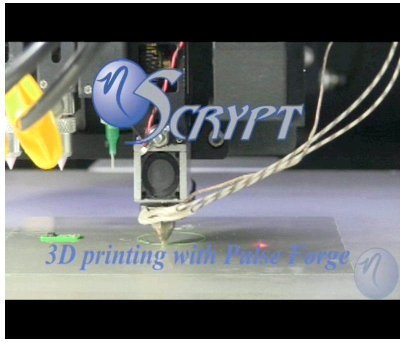


- **Printing Lab**
  - Optomec Aerosol Jet
  - nScrypt Micropen Dispenser
    - 4-head and single head
  - Sonoplot Picoliter Dispenser
  - Three 3D printers
  - Photonic Curing
  - Keyence Digital Microscope
  - 4-point probe, profilometer
- **Modeling Lab**
  - ANSYS Multiphysics bundle
- **Microwave Test Lab**
  - HP Network Analyzers (20 GHz and 50 GHz)
  - Three Wafer Probers
  - Rhodes & Schwartz Spectrum Analyzer, VNA
- **Antenna Characterization Lab**
  - Anechoic chamber
- **Packaging and Subsystem Integration**
  - Robotic Arm for printing on 3D objects





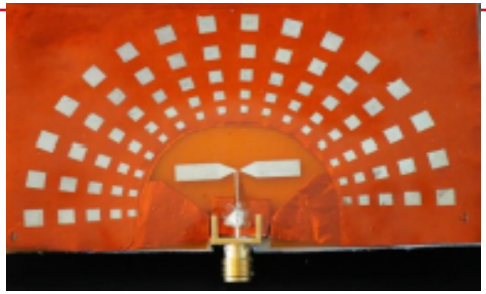




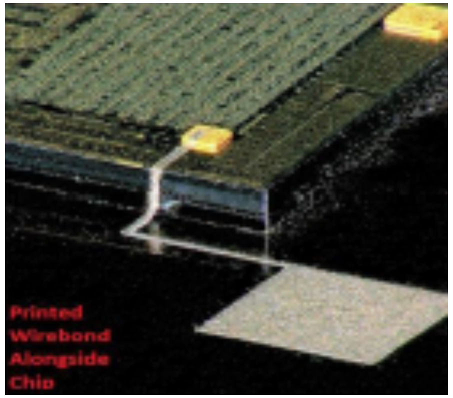
8000 sq. ft. - Access Controls in place by floor, lab and office for ITAR Projects

Research Projects

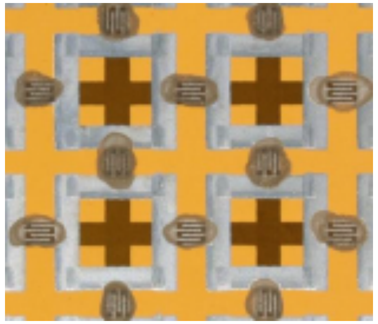
- 2D & 3D Antenna Arrays
- Additive Packaging
  - Wirebond replacement
  - Printed PCBs and via replacement
- Integrated Printed Connectors
- Tunable Frequency Selective Surfaces
- Polymer-Based Composite Substrates
- Printed Varactors
- Ferroelectric Ink Development
- Printed Phase Shifters
- Hybrid Chip Integration
- Printed CNT Transistors
- Printing on 3D Objects



Printed Metasurface Antenna



Printed Chip Interconnects

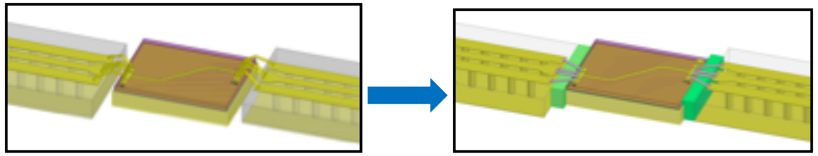


Frequency Selective Surface

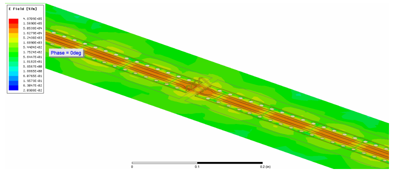
Printed X-Band Vivaldi Antenna Array

Sample Research Projects

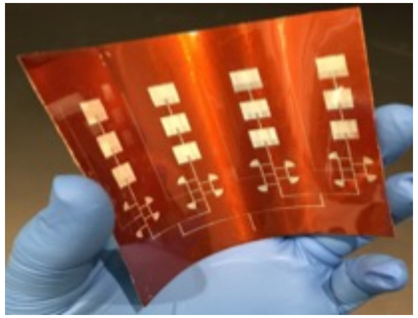
- **Chip/component integration at high frequencies**
  - Printed interconnects, wirebond replacements



- **Multi-physics Modeling**
  - Integrating electromagnetic, thermal, structural models



- **Material Characterization at High Frequencies**
  - Dielectrics, conductive materials

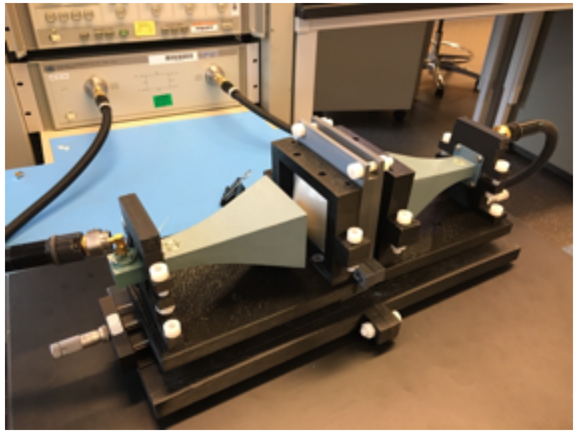


- **New Printable Materials and tunable microwave devices**
  - Ferroelectric ink, printed varactors, phase shifters, phased arrays

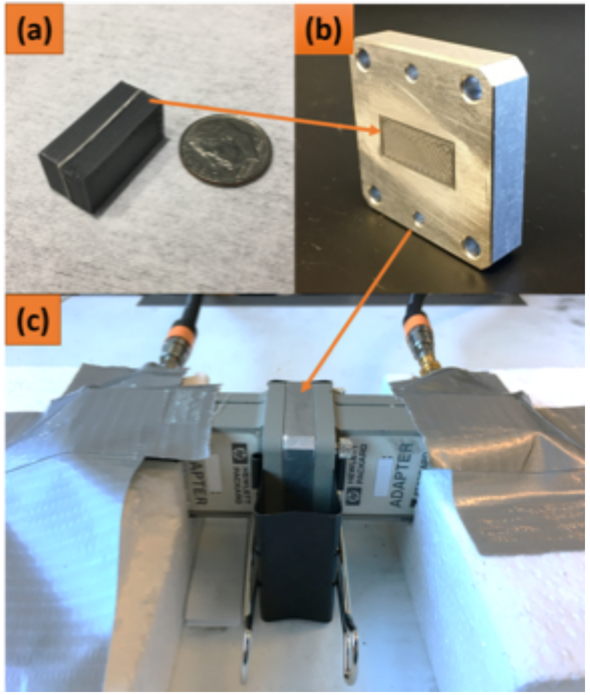
- **Printed, Integrated Connectors**
  - Printed connectors integrated with printed modules/PCBs.

Material Characterization: Dielectric Constant vs. Frequency

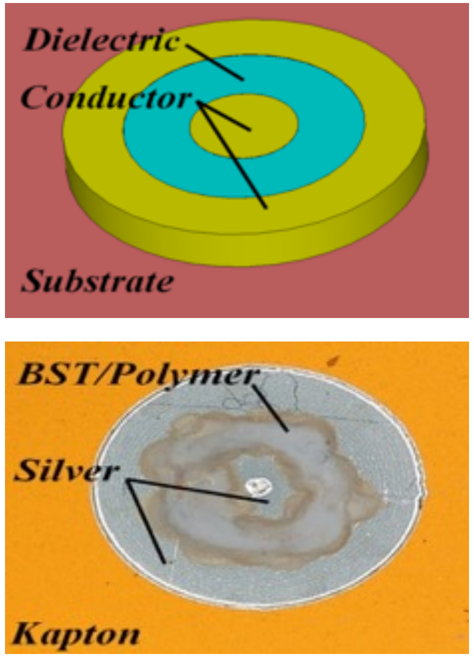
Developed new characterization techniques for measuring the dielectric constant and loss tangent of novel composite polymer substrates and inks over a wide range of frequencies.

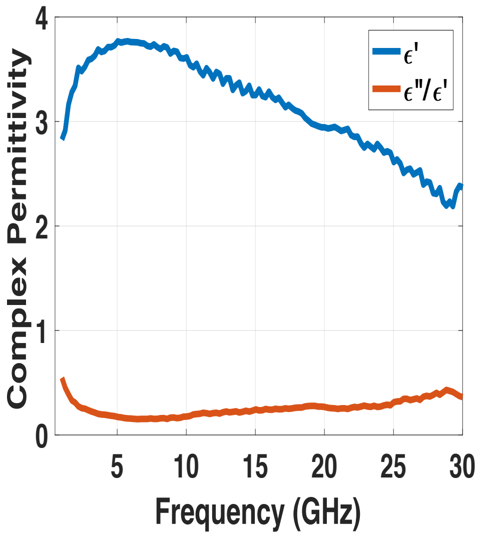


Films: Free-space characterization
3D printed apparatus designed for holding polymer films. Lenses printed for focusing microwave excitation for S-parameter measurements



Solids: Waveguide Method:
Dielectric blocks inserted PLA blocks and sample inside the flange (c) Waveguide measurement setup





Dielectric ink characterization
Printed concentric capacitors developed to extract dielectric properties. Easy sample preparation and suitable for low viscosity materials.

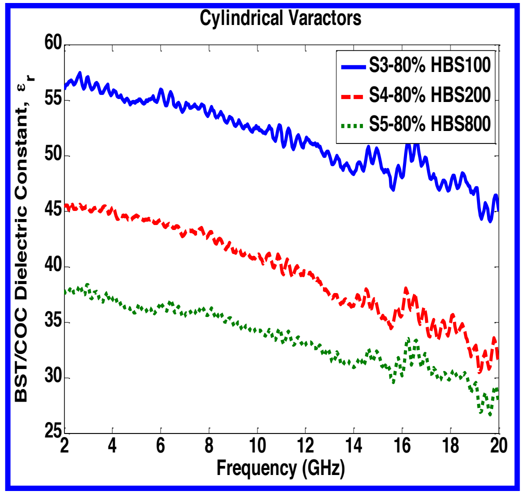
New Material Development: Ferroelectric Ink

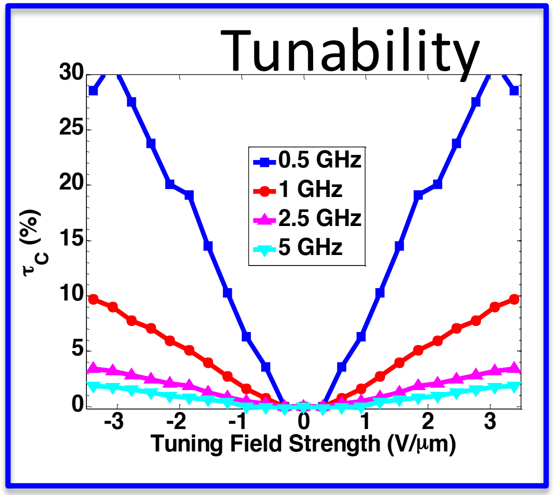
- Tunability is important in many RF/Microwave systems – e.g. tunable frequency selective surfaces (FSS) and phase shifters for phased array applications
- A printable variable capacitor (varactor) fabricated at low temperatures is needed
- Ferroelectric materials are high temperature ceramic materials
- A printable ferroelectric ink has been developed- processed at < 200°C

Barium Strontium Titanate (BST) nanoparticles in Polymer

$Ba_{0.5}Sr_{0.5}TiO_3$ particles (<100 nm)

Topas® cyclic olefin copolymer (COC 5013) polymer





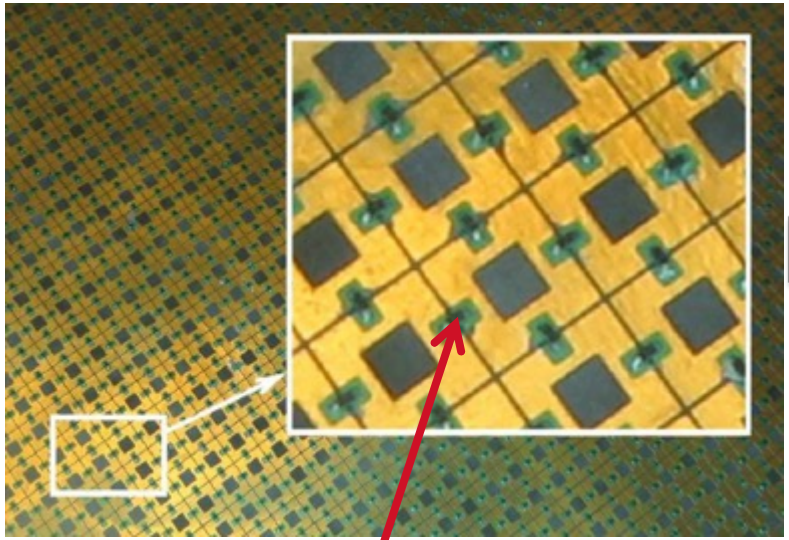
Results

- **Dielectric constant can be varied with BST particle size, composition and loading**
- **High dielectric constants can be achieved (55)**
- **Low loss tangent (~0.0005) measured**
- **10% tunability of dielectric constant up to 10 GHz**

Application: Tunable Frequency Selective Surface (FSS)

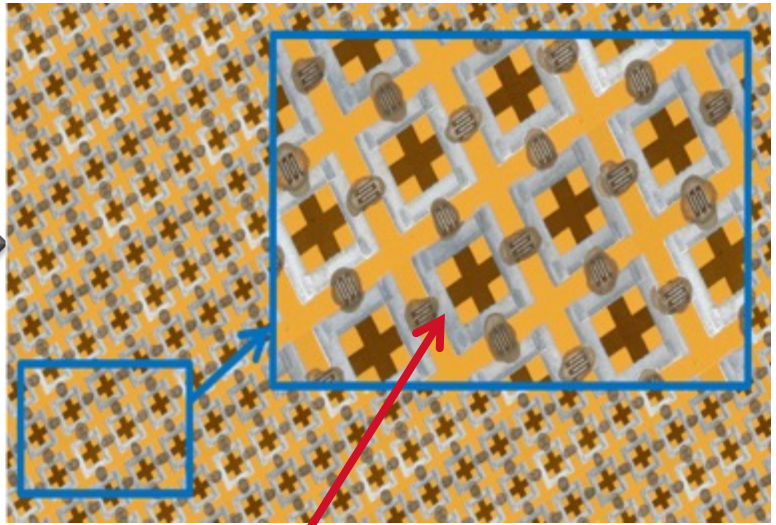
A frequency-selective surface (FSS) is an electromagnetic filter. It's frequency of operation is determined by the value of coupling capacitance between elements. The frequency response can be made **tunable** by using varactors (**var**iable capa**citors**) between circuit elements.

Rigid PCB-based FSS with surface mounted varactor diodes between elements. This approach is labor intensive and not scalable to large areas

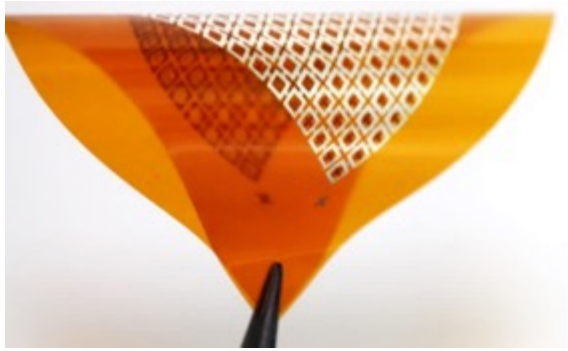


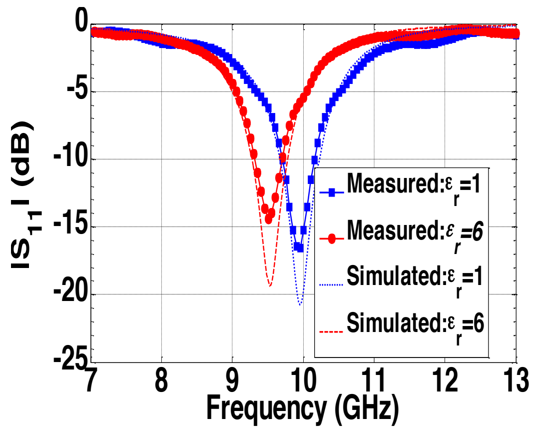
Surface mount varactor

Flexible, tunable FSS printed on Kapton with printed varactors between elements



Printed varactor

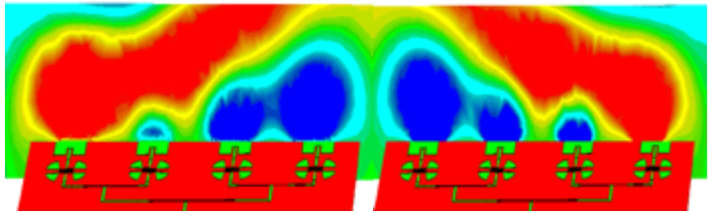


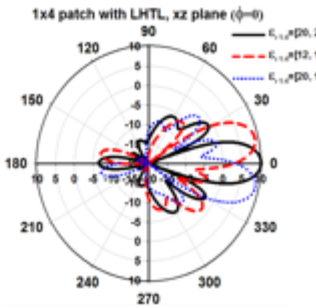


Printed Phased Array Antennas

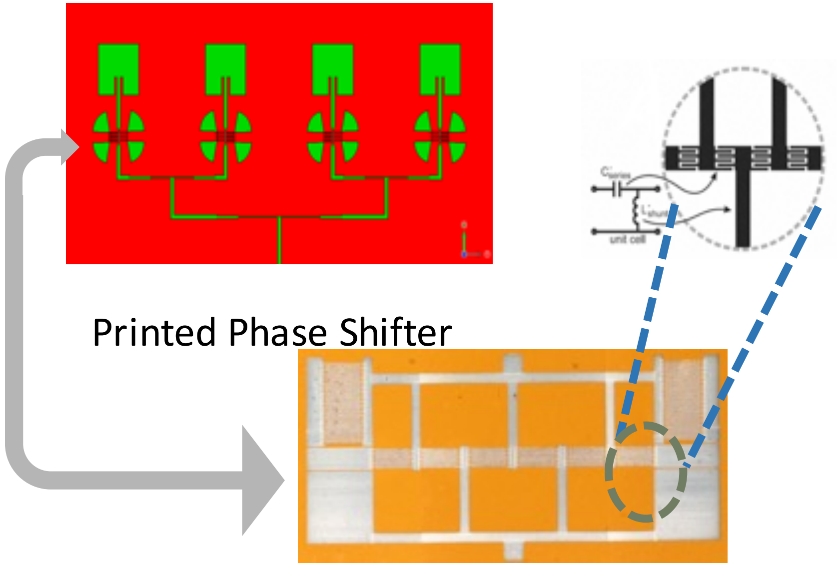
- Modelled array beam steering
- Print antennas and phase shifters on flexible substrate
- Phase shifters enabled through use of ferroelectric ink
- Adjust phase shift by applying DC bias across printed phase shifter
- Microstrip Left Hand Transmission Line (LHTL) with Radial Stub (virtual grounds)

Modelled array beam steering

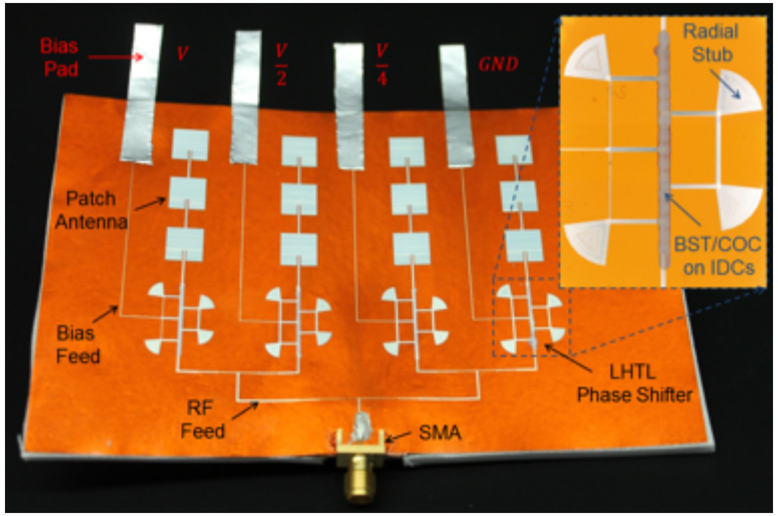




Array design including Phase Shifters



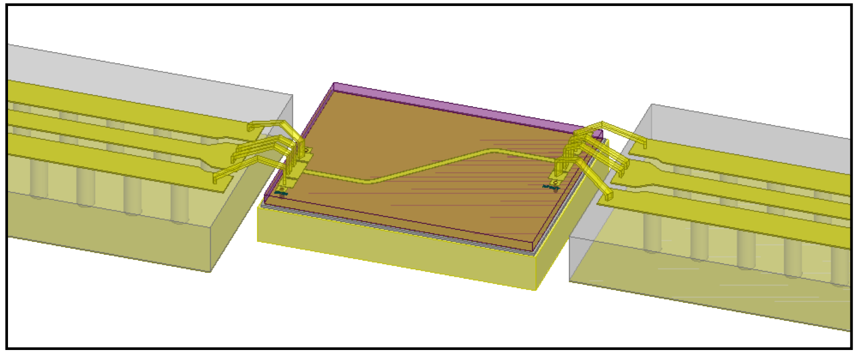
Printed Phased Array on Kapton

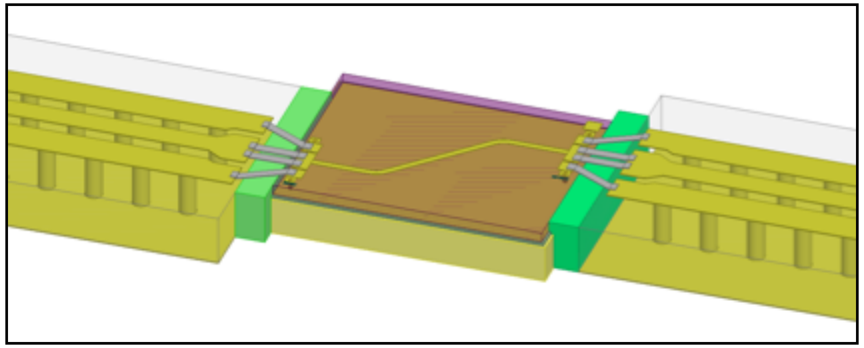


Novel Ferroelectric Ink Enables an All-Printed Phased Array

Additive Packaging: Printed Chip Interconnects

- Additively write conductive interconnects between transmission lines and microchips to replace ribbon and wire bonds.
  - Issues with inductance of wire & ribbon bonds.
  - Uncontrolled impedance.
  - Problems fitting large bonding tool in small areas to form bonds in microwave devices.
- This requires a multiphysics approach:
  - Dielectric ink used to print the interconnects on top of must be able to function electrically, thermally and structurally to maintain the integrity of the components surrounding the material





Integrated Design Tools for Printed Interconnects

Design tools should enable integration of electromagnetic, thermal and structural models

Electromagnetic Models (HFSS)

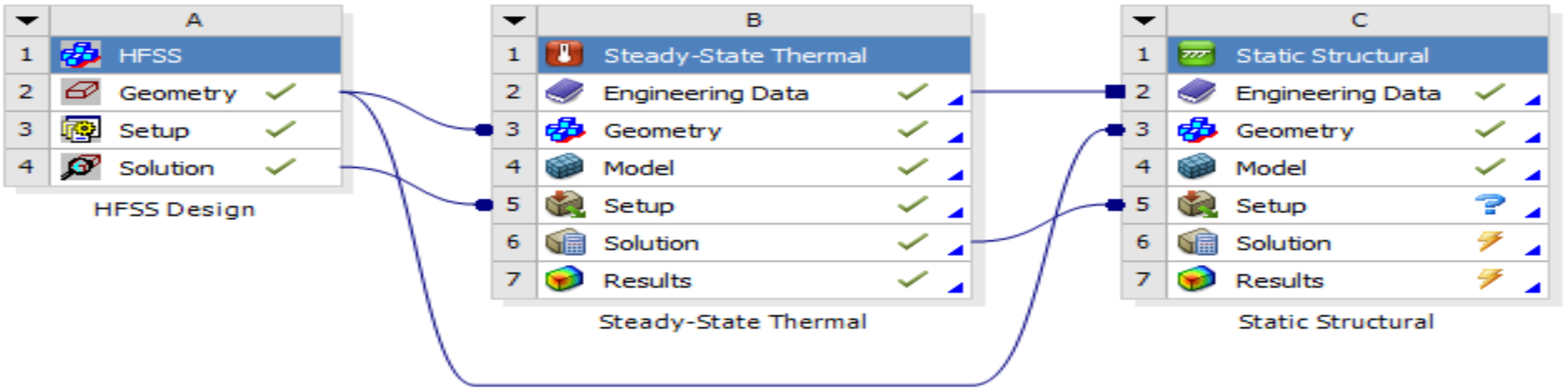
- Frequency sweeps of device performance
- Optimize choice of materials
- Important results include S parameters and visualization of E and H fields

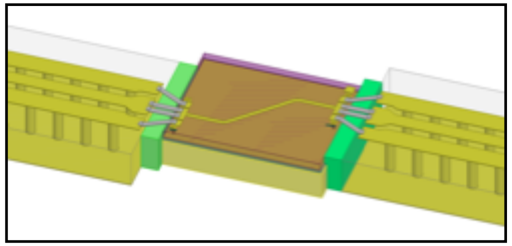
Steady State Thermal

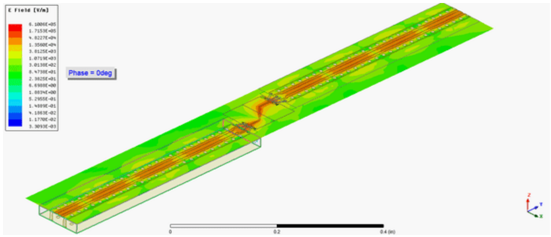
- Results from HFSS are applied to conduct temperature analysis
  - Thermal conductivity and other material properties of materials are used to generate 'heat map' of device, showing temperature and heat flux images

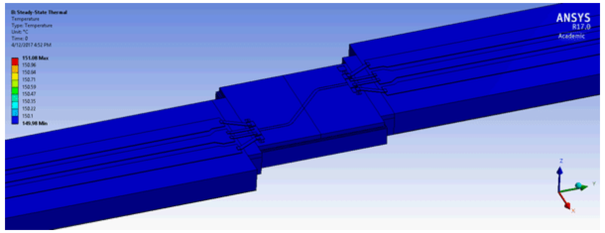
Static Structural

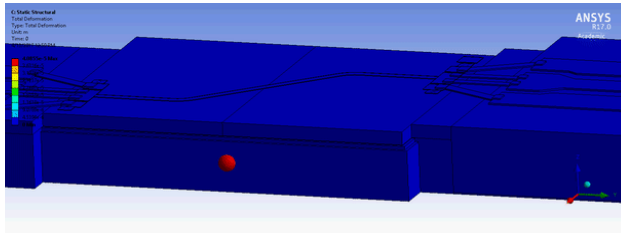
- Stress caused by thermal expansion
  - Thermal expansion coefficient, Young's modulus and other material properties used to show where the most stress is applied to device under heated conditions







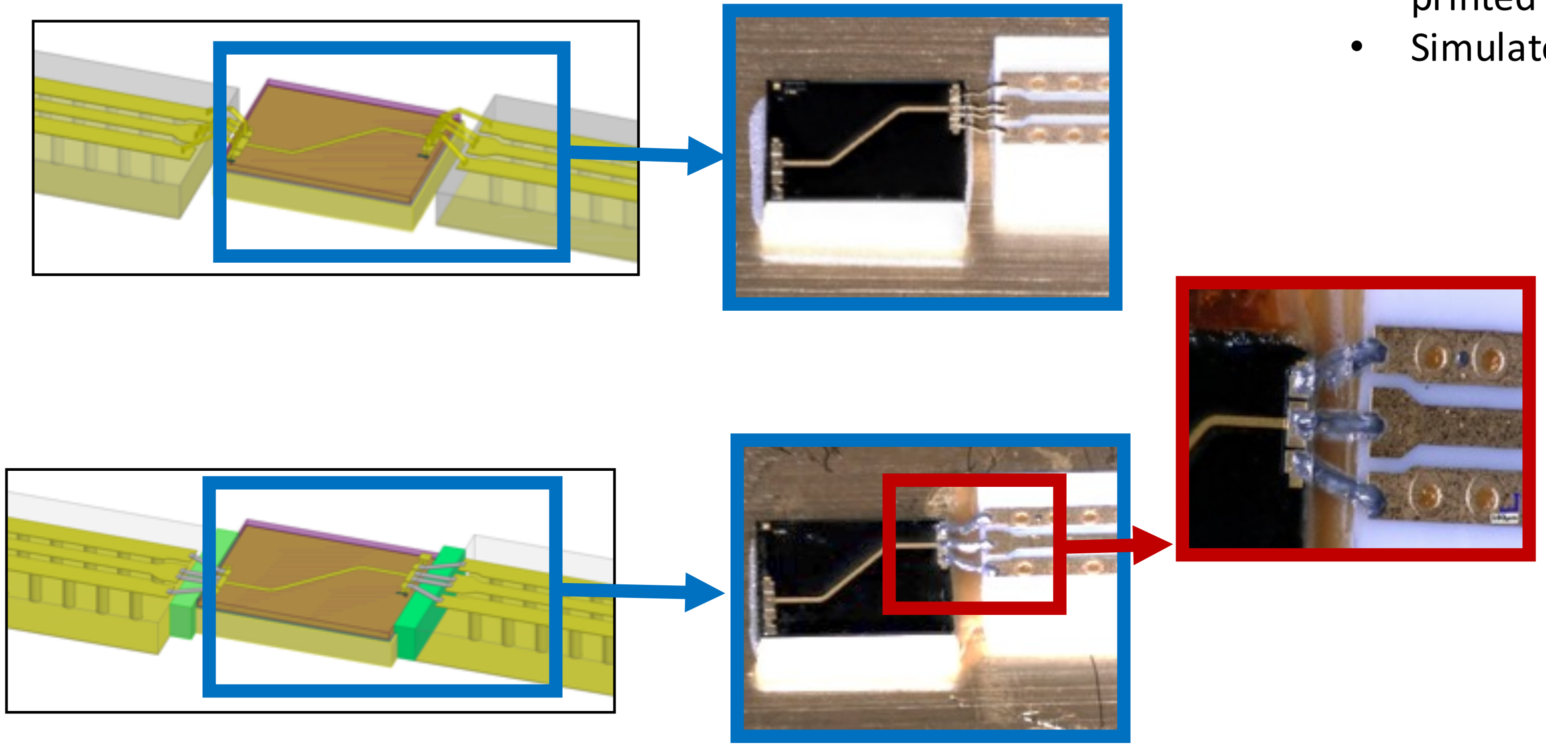


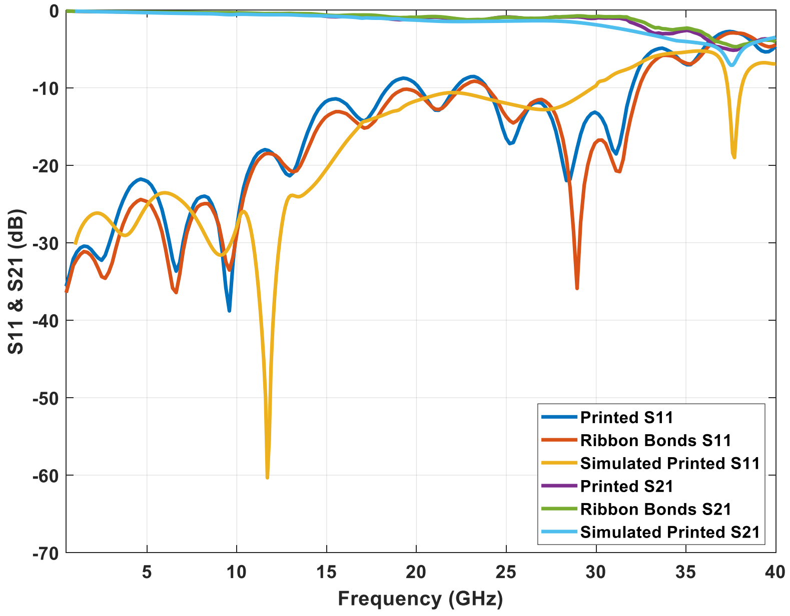


Measured Ribbon Bonds vs Printed Interconnects

The frequency response of modelled and measured ribbon bonds compared with printed interconnects. Ribbon bond Interconnects between a coplanar waveguide (CPW) on alumina and GaAs microchip.

- Very good correlation of microwave measurements between printed and ribbon bond interconnects
- Simulated results in good agreement with measured results.

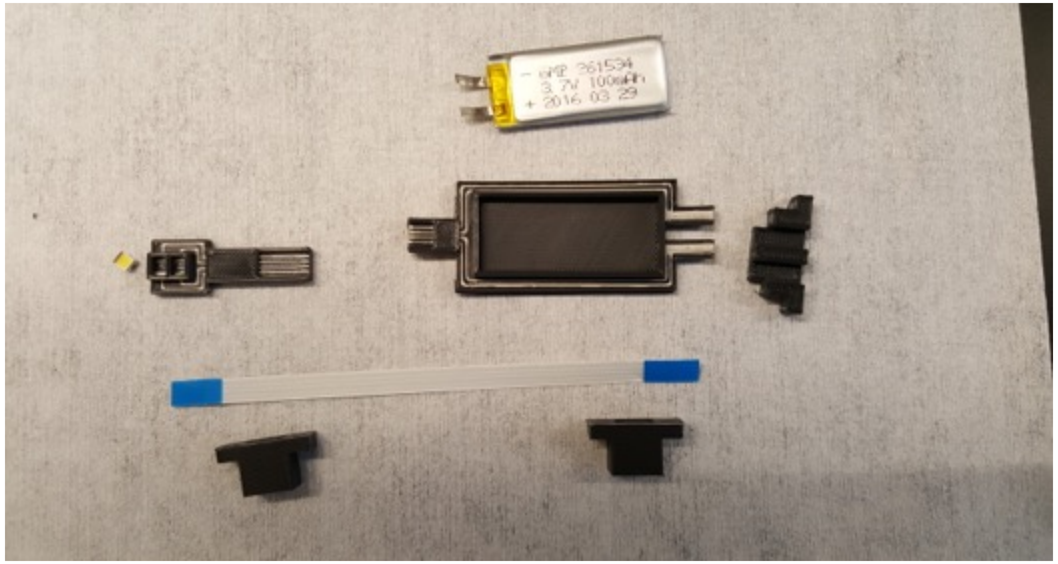


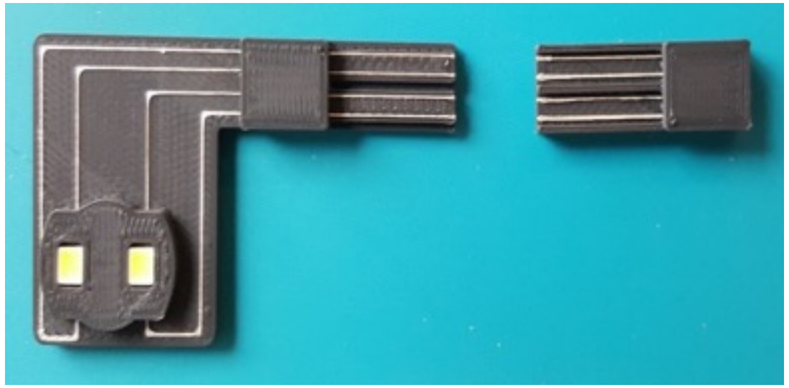


Printed Interconnects show promising performance up to X-Band

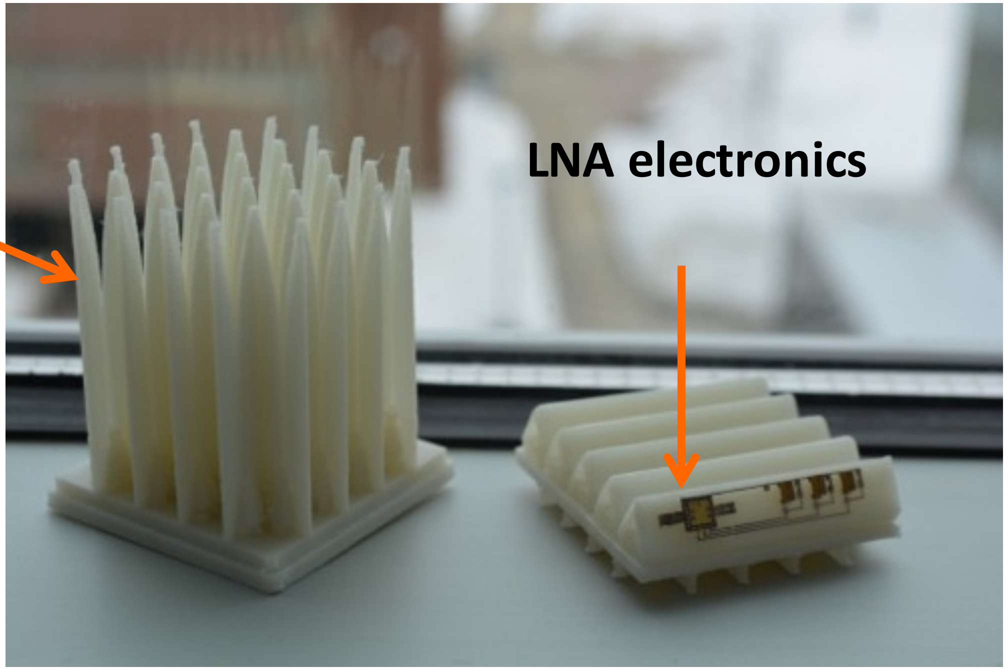
Additive PCBs and Connectors

- Connectors and small PCBs can be printed in a hybrid system (thermoplastics and conductive traces). Connectors employ printed mechanical features to align conductive traces.
- PCBs can be printed with integrated connectors

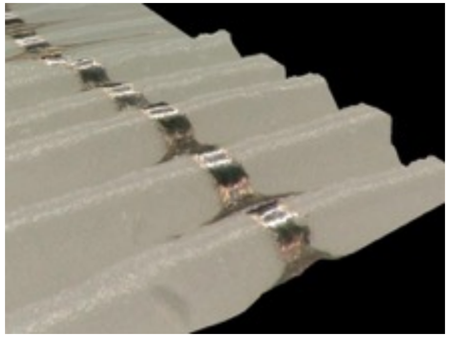




3D Additive RF Systems: Low Cost X-Band Antenna Arrays



Printed conductive trace on 3D-printed surface



Surfaces not flat enough for fine conductive traces

- Focus on low cost approaches for broadband antennas
- Vivaldi antenna design at X-Band
- Thermoplastics printing to create physical scaffolding for Vivaldi antenna array
- Developing chip attach and printed interconnect on thermoplastics

Final Thoughts

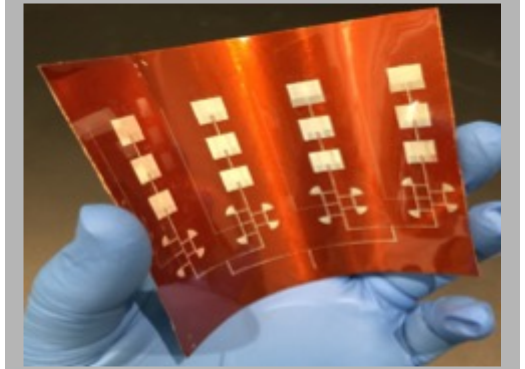
- Printed Electronics for microwave applications is in the “Wild West” phase
  - Incoherent supply chain
  - Lack of standards, materials, models, SW
  - Development of printed subsystems in the microwave domain introduces additional challenges in every phase (design, materials, printing & characterization)

- Will need to develop the supply chain for PE technology similar to IC manufacturers in the 60’s & 70’s
- Partnerships between companies, government (state and federal) and universities can accelerate the build out of the ecosystem for printed electronics

RURI and PERC bring industry, academia and supply chain together to accelerate innovation and adoption of printed electronics for microwave applications.

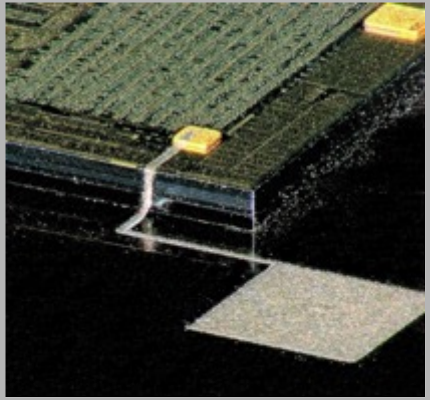
PE Form Factors and Printing Technology

2D



Flexible, conformable
Plastic or paper substrates
Micropen Dispensers

2.5D



Flex-Hybrid systems add active components
Aerosol jet printers

Printing 3D

Print 3D structures with electronics
Multiple printers (3D+aerosol) OR Hybrid (multihead) system

Printing on 3D

Print electronics on existing 3D structures
Micropen with surface mapping OR Robotic arm

Multiple types of printing systems may be required depending on the form factor, printed features sizes, and the materials required to build the device/system