“Zero-Power” Additively Manufactured FHE-Enabled Wireless/5G+ Ultrabroadband Modules for IoT, SmartAg, Industry 4.0 and Smart Cities Applications: from Dream to Reality

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ATHENA Lab Overview

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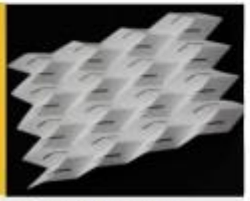
Low-cost Nanomaterial-Enabled Sensors and Switches

- Selectively functionalized CNT/graphene-based gas sensors for real-time environment monitoring
- CNT-based RF switches for flexible, fully printed phased arrays

Printed "Smart" 3D Wireless Packaging

- Inkjet printed ramped interconnects on a 3D printed packaging structure
- 3D printed system-on-antenna (SoA) with fully integrated RF front end.

Reconfigurable 4D Origami-Inspired Structures



- Tunable frequency selective surfaces using 3D miura folding with paper
- Compressible/stretchable 3D antennas with liquid metal conductors and 3D scaffolding

Long-Range RFID and Energy Harvesting

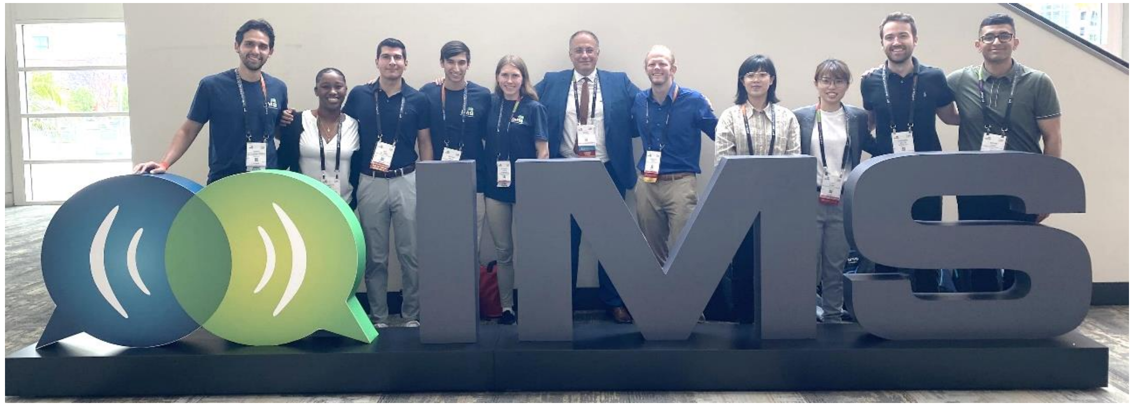
- Km-range passive "smart-skin" RFID sensors with mm-wave reflectarray
- Wearable UHF energy harvesting systems for wireless on-body IoT devices

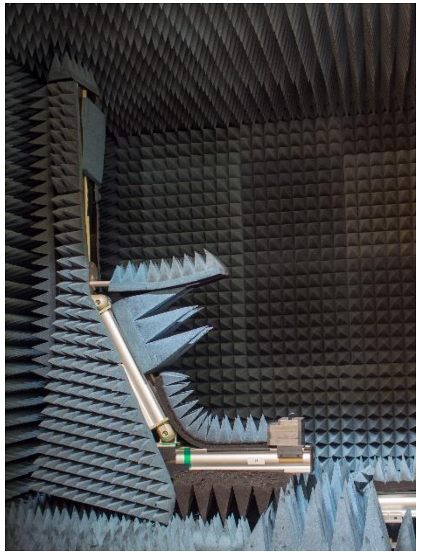
Fully Printed Flexible RF/5G+/mmW Modules

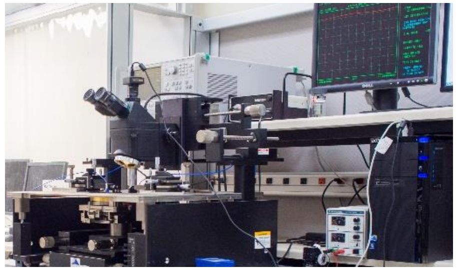
- Full RF system including antennas, rectifiers, microfluidics in a flexible compact package
- Fully inkjet printed Massively scalable 5G antennas/modules.

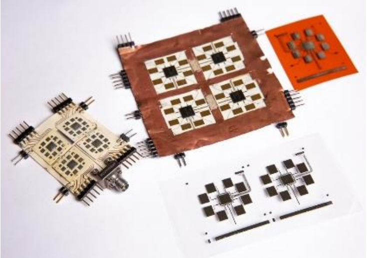
Flexible Printed Lenses and Wireless Power transfer systems

- Rotman Lens for mm-wave/5G power transferring and communication
- Breaking the high gain and large beamwidth trade-off at mm-wave frequencies



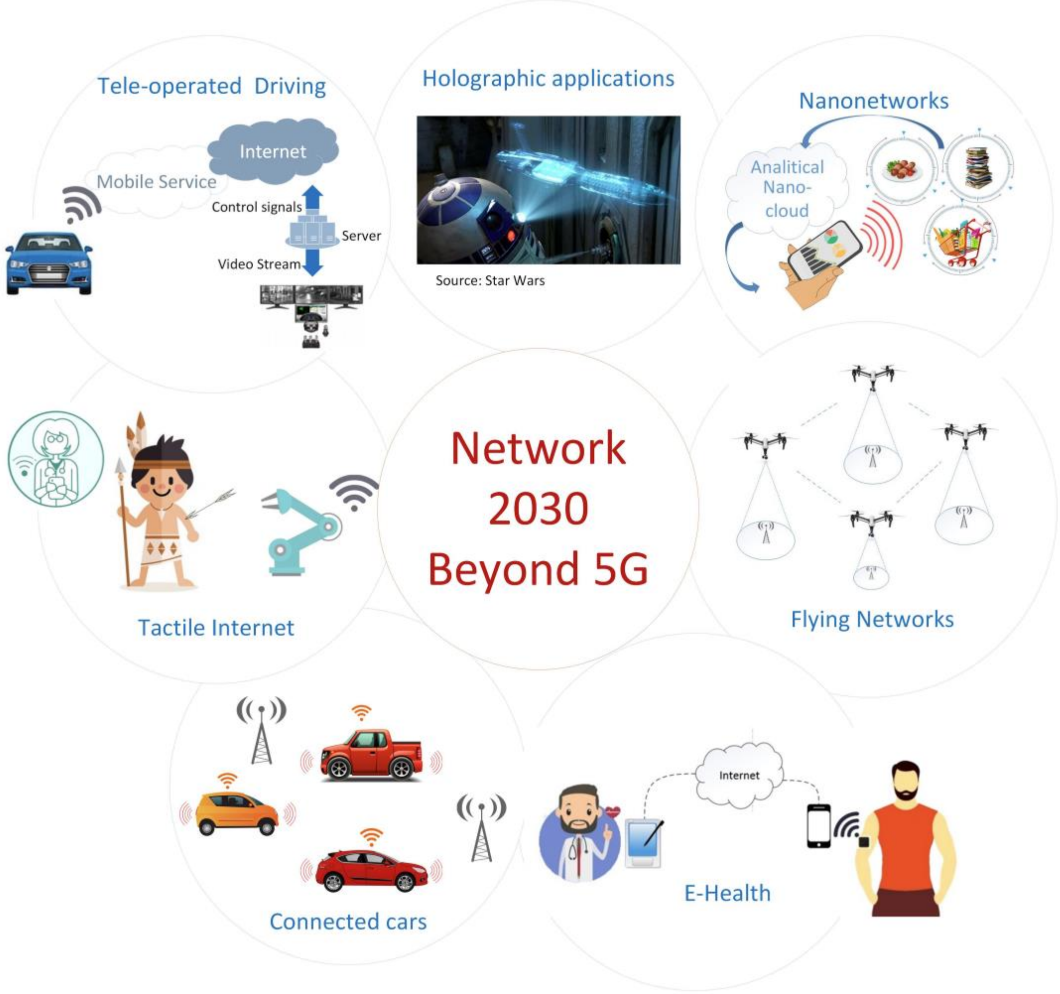




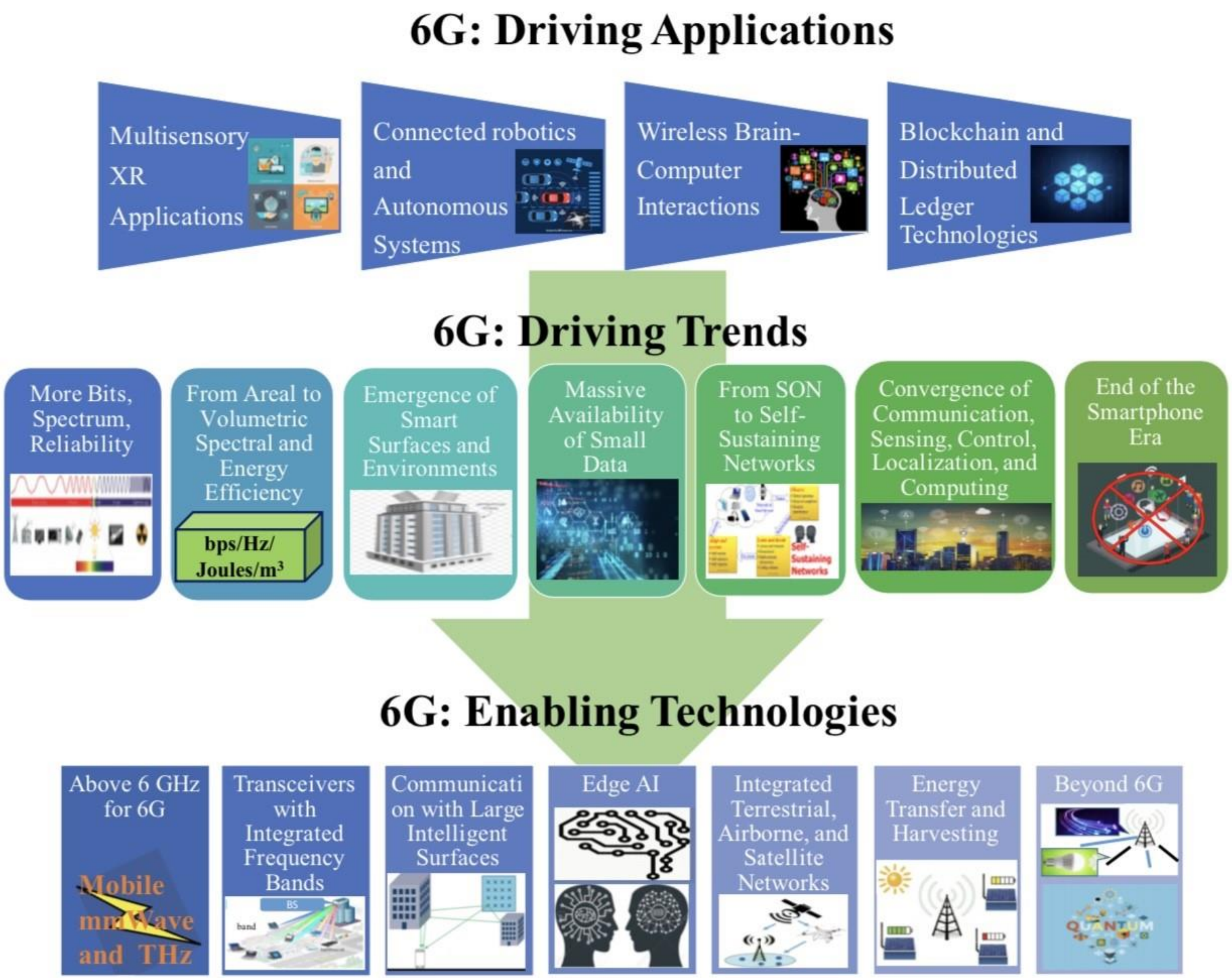


6G Applications

- Human-centric mobile applications
- Active indoor positioning
- On-board/underwater communications
- Wearable devices/implantable sensors
- Holographic/Interactive virtual reality
- Smart/remote medical service
- Robotic/Vehicular communications



- Dang, S., Amin, O., Shihada, B. et al. What should 6G be?. Nat Electron 3, 20–29 (2020). https://doi.org/10.1038/s41928-019-0355-6
- A. Yastrebova, R. Kirichek, Y. Koucheryavy, A. Borodin and A. Koucheryavy, "Future Networks 2030: Architecture & Requirements," 2018 10th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), Moscow, Russia, 2018, pp. 1-8, doi: 10.1109/ICUMT.2018.8631208.



- K. B. Letaief, W. Chen, Y. Shi, J. Zhang and Y. -J. A. Zhang, "The Roadmap to 6G: AI Empowered Wireless Networks," in IEEE Communications Magazine, vol. 57, no. 8, pp. 84-90, August 2019, doi: 10.1109/MCOM.2019.1900271.
- W. Saad, M. Bennis and M. Chen, "A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems," in IEEE Network, vol. 34, no. 3, pp. 134-142, May/June 2020, doi: 10.1109/MNET.001.1900287.

6G Specifications

- High intelligence for human-centric applications
- High security, secrecy and privacy
- High affordability and full customization
- Technical requirements
    - THF (FCC opens 95GHz-3THz)
    - Ultra-wide bandwidth
    - Low latency (1 ms end-to-end)
    - Wide 3D coverage
    - Very high data rate (1Tb/s)
    - High energy efficiency (batteryless)

	5G	Beyond 5G	6G
Application types	• eMBB •URLLC •mMTC	• Reliable eMBB •URLLC •mMTC •Hybrid (URLLC + eMBB)	New applications: • MBRLLC • mURLLC • HCS • MPS
Device types	• Smartphones • Sensors • Drones	• Smartphones • Sensors • Drones •XR equipment	• Sensors and DLT devices • CRAS • XR and BCI equipment • Smart implants.
Spectral and energy efficiency gains[1] with respect to today's networks	10x in bps/Hz/m^2/Joules	100x in bps/Hz/m^2/Joules	1000x in bps/Hz/m^3/Joules (volumetric)
Rate requirements	1 Gb/s	100 Gb/s	1 Tb/s
End-to-end delay requirements	5 ms	1 ms	< 1 ms
Radio-only delay requirements	100 ns	100 ns	10 ns
Processing delay	100 ns	50 ns	10 ns
End-to-end reliability requirements	99.999 percent	99.9999 percent	99.99999 percent
Frequency bands	• Sub-6 GHz • MmWave for fixed acces.	• Sub-6 GHz • MmWave for fixed access	• Sub-6 GHz • MmWave for mobile acces • Exploration of higher frequency and THz bands (above 300 GHz) • Non-RF (e.g., optical, VLC, etc.)
Architecture	• Dense sub-6 GHz small base stations with umbrella macro base stations. • MmWave small cells of about 100 m (for fixed access).	• Denser sub-6 GHz small cells with umbrella macro base stations • < 100 m tiny and dense mmWave cells	• Cell-free smart surfaces at high frequency supported by mmWave tiny cells for mobile and fixed access. • Temporary hotspots served by drone-carried base stations or tethered balloons • Trials of tiny THz cells.

[1] Here, spectral and energy efficiency gains are captured by the concept of area spectral and energy efficiency.

TABLE 1. Requirements of 5G vs. Beyond 5G vs. 6G.

- K. B. Letaief, W. Chen, Y. Shi, J. Zhang and Y. -J. A. Zhang, "The Roadmap to 6G: AI Empowered Wireless Networks," in IEEE Communications Magazine, vol. 57, no. 8, pp. 84-90, August 2019, doi: 10.1109/MCOM.2019.1900271.
- W. Saad, M. Bennis and M. Chen, "A Vision of 6G Wireless Systems: Applications, Trends, Technologies, and Open Research Problems," in IEEE Network, vol. 34, no. 3, pp. 134-142, May/June 2020, doi: 10.1109/MNET.001.1900287.

Potential Technologies

- Terahertz communication with UWB operation
- Machine learning enabled intelligent radio
- Flexible hybrid electronics for wearables
- Reconfigurable Intelligent Surface
- Wireless charging using energy harvesting
- Additive manufacturing with low cost and high customization

State-of-art Review

Attribute	Paper					
	Yang et al., [8]	Zhang et al., [2]	Saad et al., [4]	Giordani et al., [5]	Strinati et al., [3]	This article
Peak data rate	1 Tb/s	1 Tb/s	1 Tb/s	5 Tb/s (for VAR)	1 Tb/s	1 Tb/s
Backhaul Data Rate	×	10 Tb/s	×	×	×	10 Tb/s
Volumetric Capacity	×	×	✓	×	1–10 Gb/s/m3	✓
Operating Frequency	0.06 to 10 THz	Up to 10 THZ	300GHz + Visible Light Frequency (VLF)	100GHz to 10THz + VLF	Sub THz band + VLF	Up to 1 THz + VLF
Mobility	×	≥ 1000km/h	×	1000 km/h	×	1000 km/h
Latency	≤ 1ms	0.01–0.1ms	≤ 1ms	≤1ms	1ms	Cplane: ≤ 1ms Uplane: ≤ 0.1ms
Major Use Cases	Fine Medicine, Intelligent Disaster Prediction, Surreal VR, 3D Videos	Holographic Projection, Tactile and Haptic, Autonomous Driving, Internet of Nano-Bio Things, Space Travel	XR (VR/AR), Brain Communication, Connected Robotics & Autonomous Systems	Teleportation, eHealth, VAR, Industry 4.0, Robotics, Autonomous Transportation	High Precision Manufacturing, Smart Environment, Holographic Communication	Remote Surgery, Haptic Comm, Massive IoT Enabled Smart City, VAR, Autonomous Driving, Automation and Manufacturing
Key Enabling Technologies	Ultra Massive MIMO OAM-MDM, Super Flexible Integrated Network, Multi-Domain Index Modulation	THz Communication, Holographic Beamforming, Quantum Comm, AI/ML, LIS, VLC Blockchain	Tinycell, Ubiquitous Network Energy Transfer and Harvesting, Transceiver with Integrated Frequency Band, Smart Surface	THz Communication, VLC, ML, 3D Networks, Cell-less Architecture, Energy Harvesting NFV, Backhaul	Novel Network Architecture, VLC, AI at Network Edge, Battery-less Devices, THz Communication, Distributed Security	THz Communication, Pervasive AI, EH, VLC, Blockchain, Cell Free Network, Quantum Comm, Metasurface, OAM, WPT, Context. Comm.

TABLE 3. A comparative study among variuos 6G approaches.

[2] Z. Zhang et al., "6G Wireless Networks: Vision Requirements Architecture and Key Technologies", IEEE Vehicular Technology Mag., vol. 14, no. 3, pp. 28-41, Sept. 2019.

[3] E. Calvanese Strinati et al., "6G: The Next Frontier: From Holographic Messaging to Artificial Intelligence Using Subterahertz and Visible Light Communication", IEEE Vehicular Technology Mag., vol. 14, no. 3, pp. 42-50, Sept. 2019.

[4] W. Saad, M. Bennis and M. Chen, "A Vision of 6G Wireless Systems: Applications Trends Technologies and Open Research Problems", IEEE Network, vol. 34, no. 3, pp. 134-142, May/June 2020.

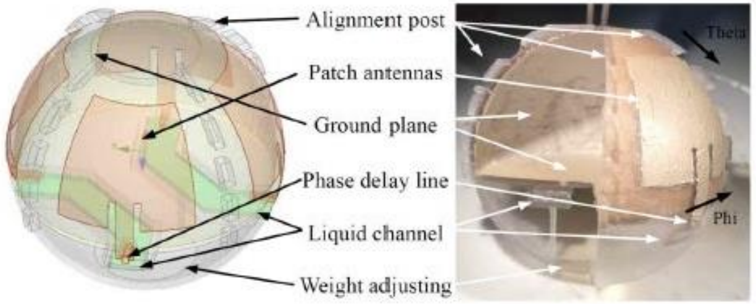
[5] M. Giordani et al., Towards 6G Networks: Use Cases and Technologies, Mar. 2019

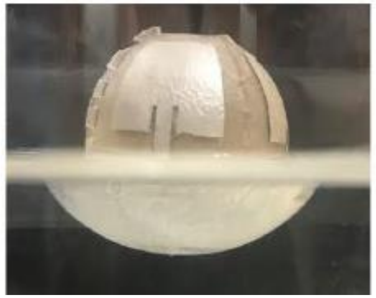
[8] P. Yang et al., "6G Wireless Communications: Vision and Potential Techniques", IEEE Network, vol. 33, no. 4, pp. 70-75, July 2019.

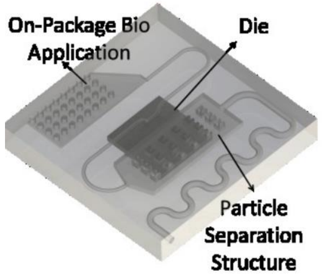
- F. Tariq, M. R. A. Khandaker, K. -K. Wong, M. A. Imran, M. Bennis and M. Debbah, "A Speculative Study on 6G," in IEEE Wireless Communications, vol. 27, no. 4, pp. 118-125, August 2020, doi: 10.1109/MWC.001.1900488.

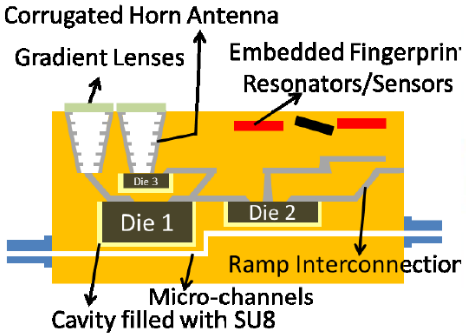
Zero-Power Environmentally-Friendly Self-Healing "Morphing" (4D) Fully-Additively Manufactured Antennas, Metasurfaces and Reconfigurable Intelligent Surfaces

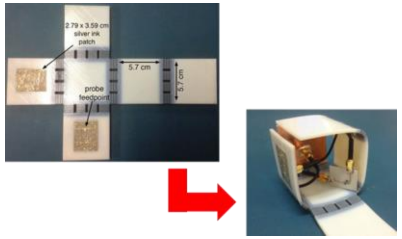
Scalable, Sustainable, Speedy, Secure and Smart ("5S" challenge).

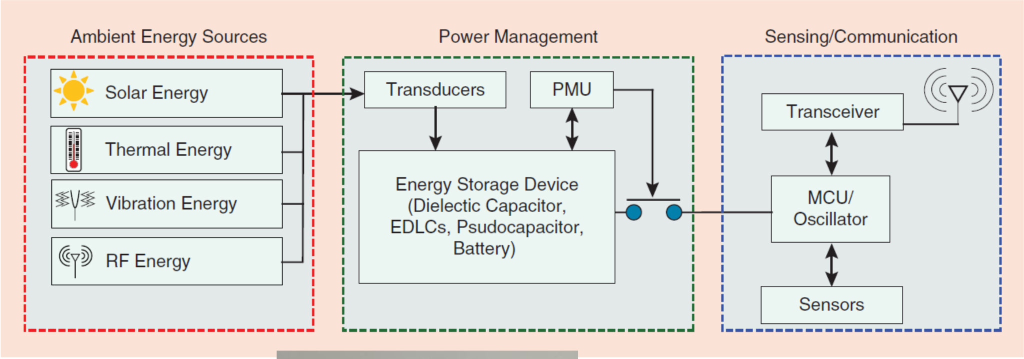


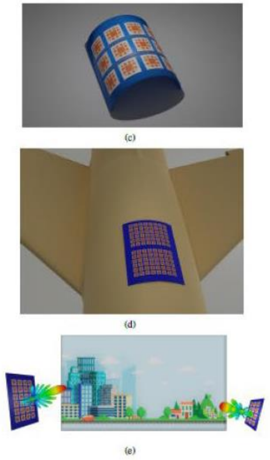


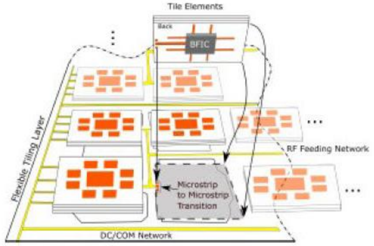


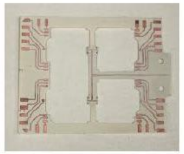


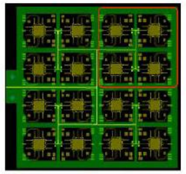


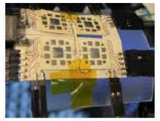


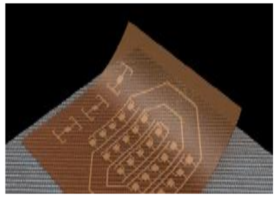


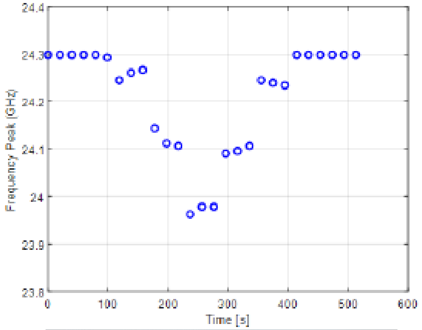


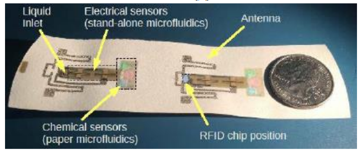


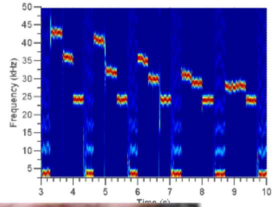


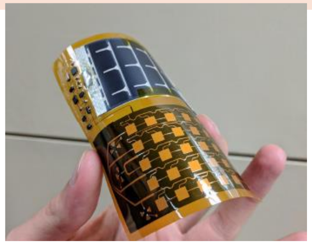


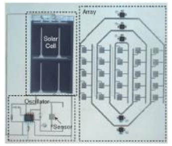


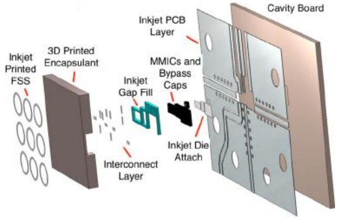


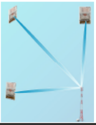












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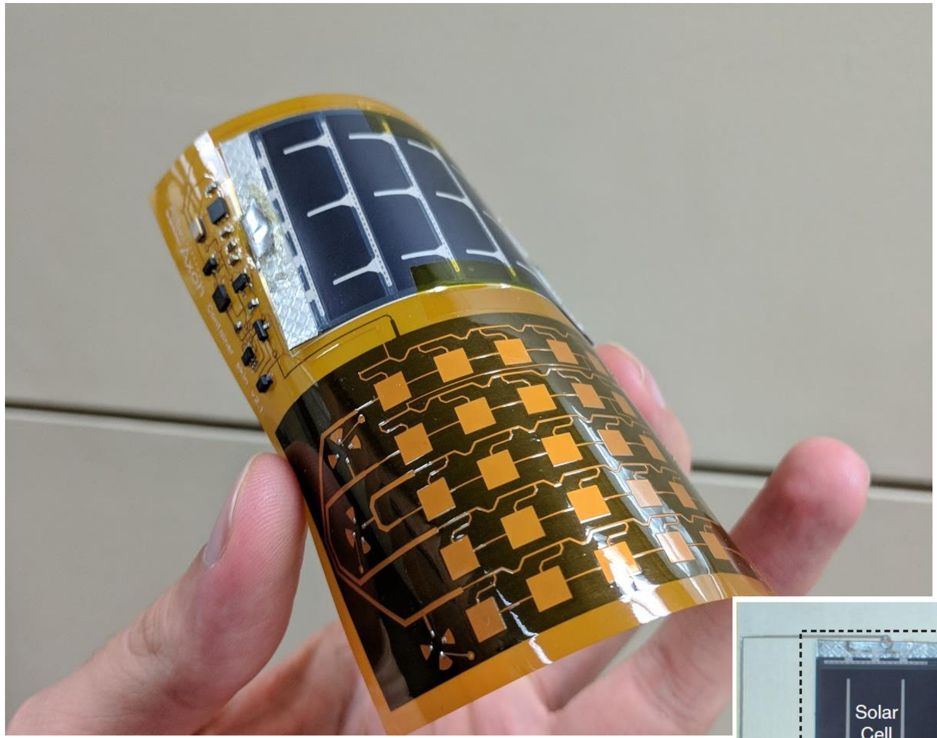
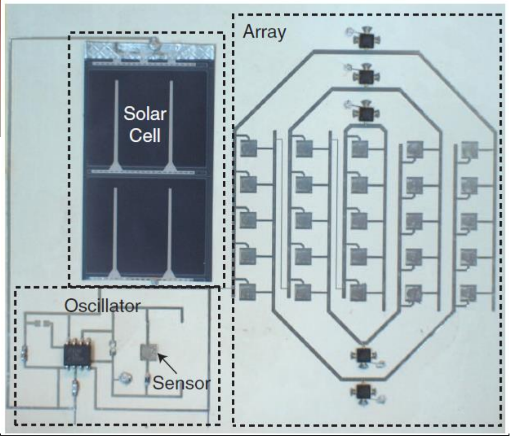
The Internet of Smart Skins

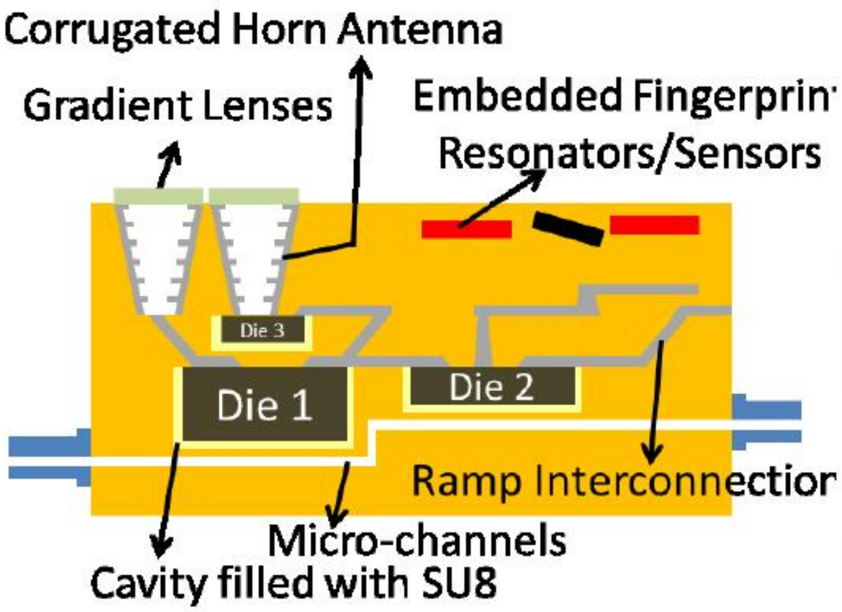
- Thin, Flexible device: the Skin
- Ultra-low-power: <20 µW
- Battery-less: Energy Harvesting
- Long-range: 250m+
- Localizable in real time (**cm accuracy**): single-reader localization (Angle+range)
- Metal-mounting compatible
- Enhanced by 5G+/6G.



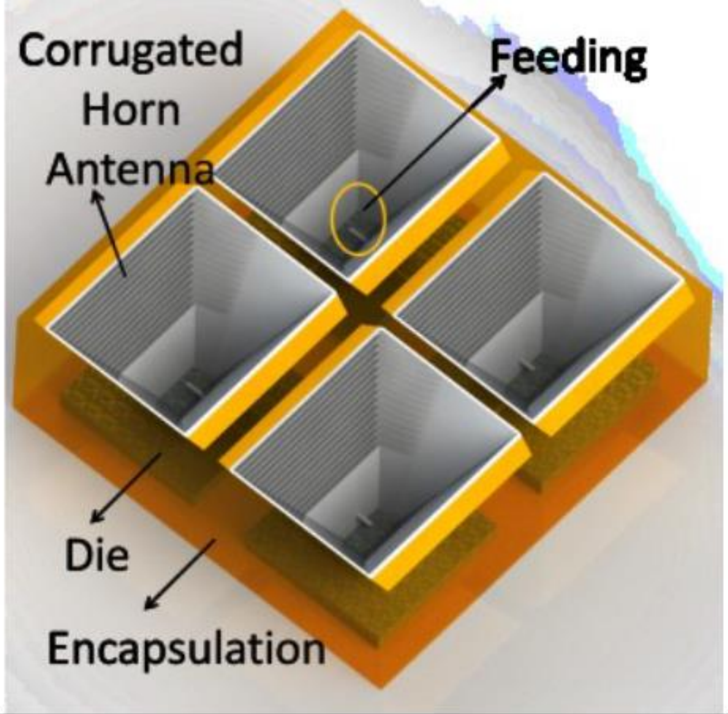


Scalable, Sustainable, Speedy, Secure and Smart (“5S” challenge)

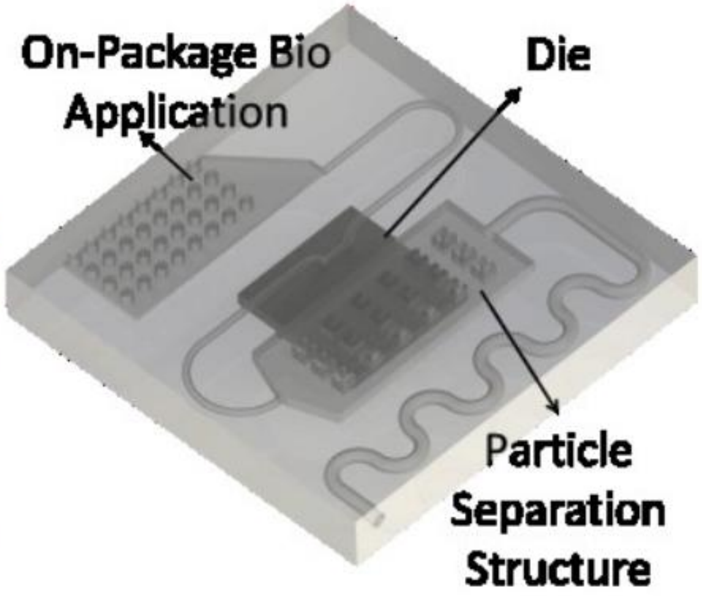
Vision: AM Smart Packaging and "Self-Healing" mmWave transceivers



Full smart package with multiple features.

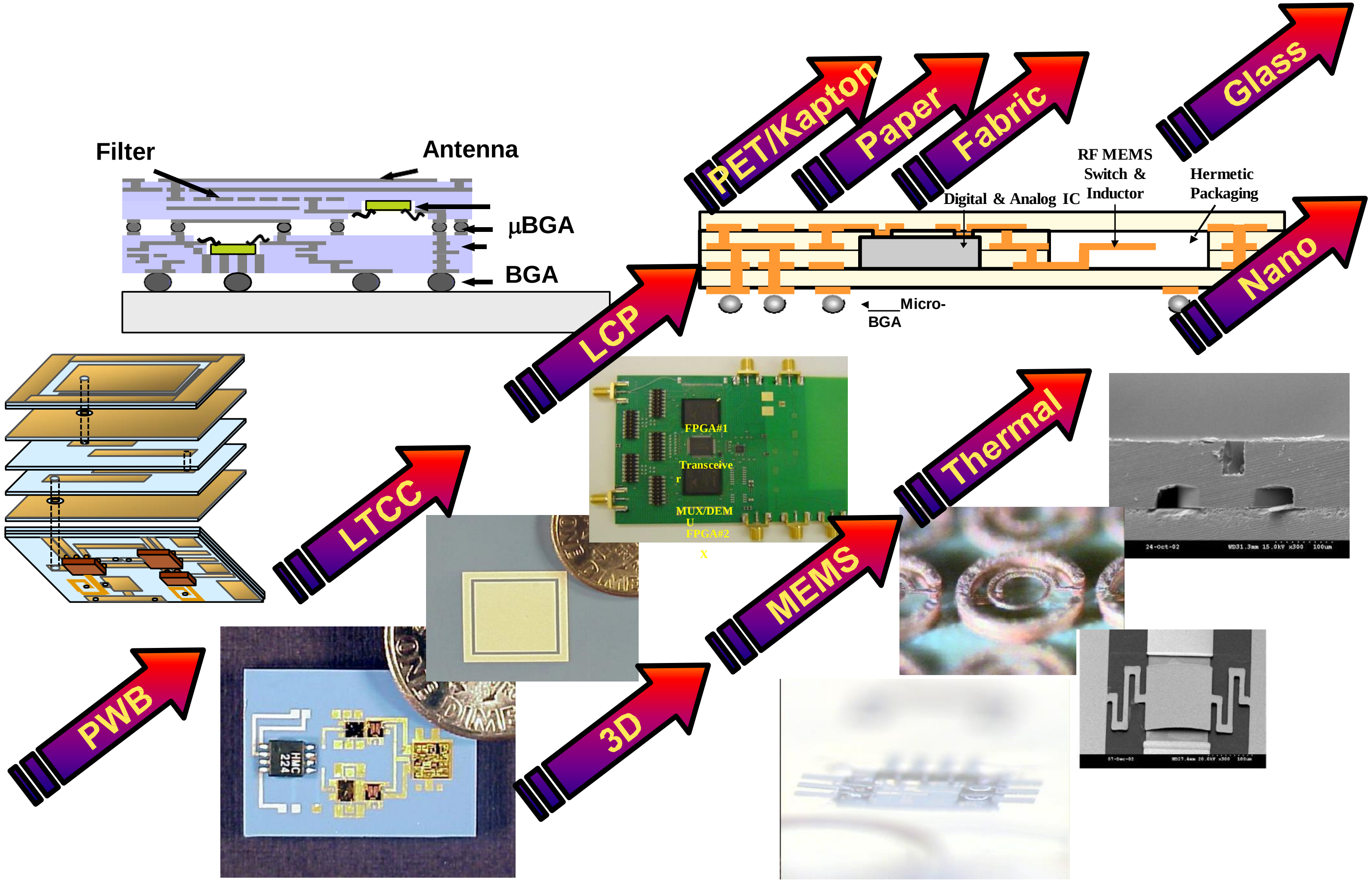


Horn antenna array integrated into MCM, for compact high gain mm-Wave transceivers.



Integration of BIOMEMS inspired structures for wearable and implantable wireless biosensors

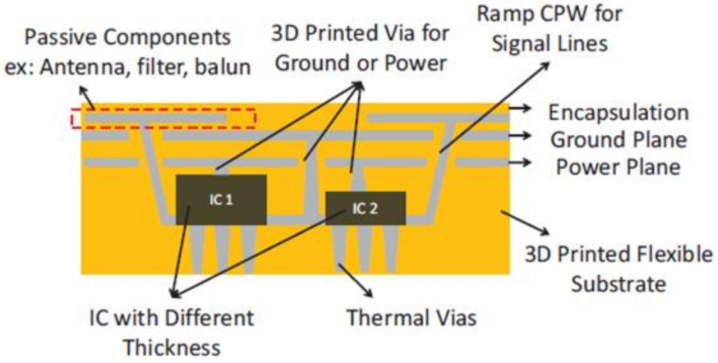
Disruptive Wireless Modules Technological Steps



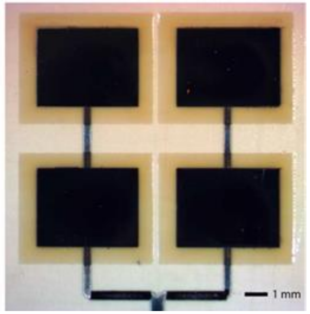
Additive Manufacturing Technologies: A Manufacturing Revolution

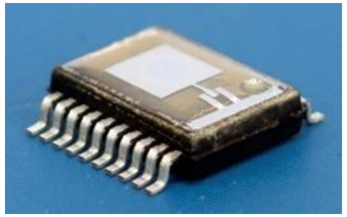
Additive Manufacturing technologies

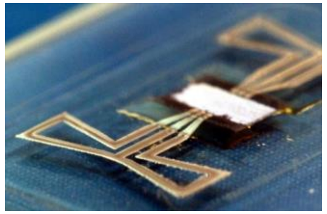
Inkjet Printing

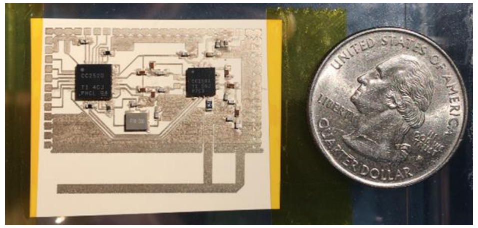


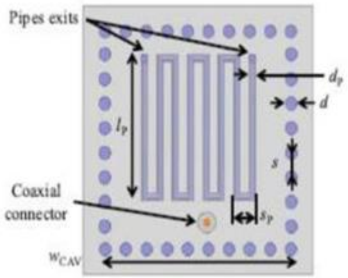
3D Printing

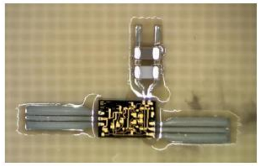


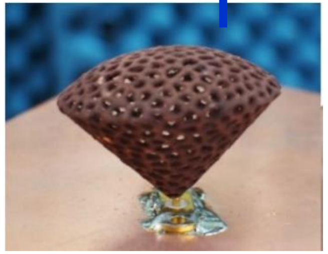


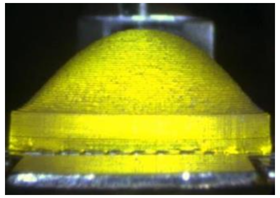


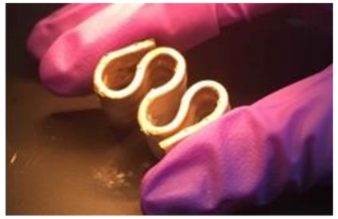


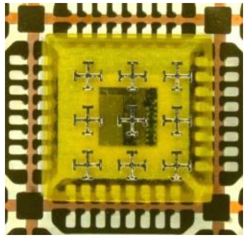


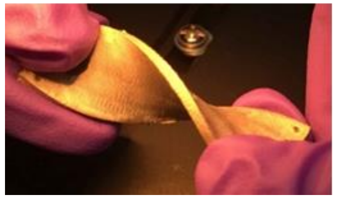




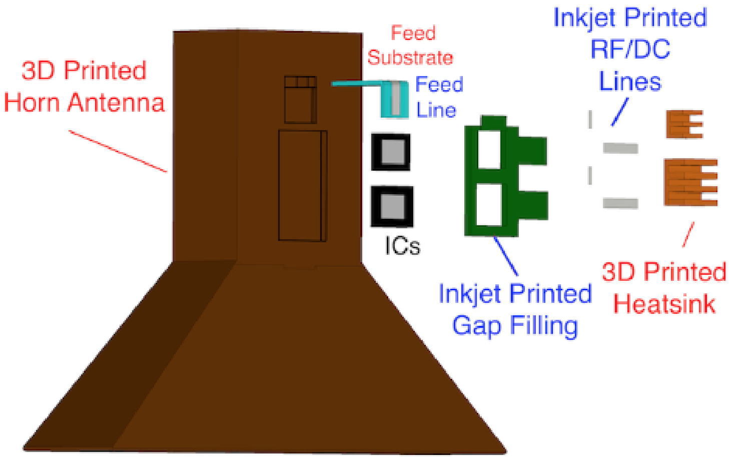


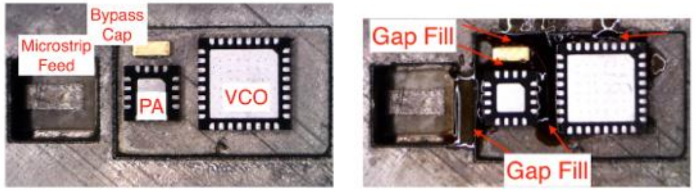






System On Antenna (SOA)





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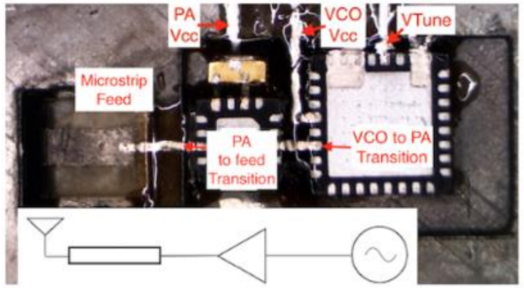
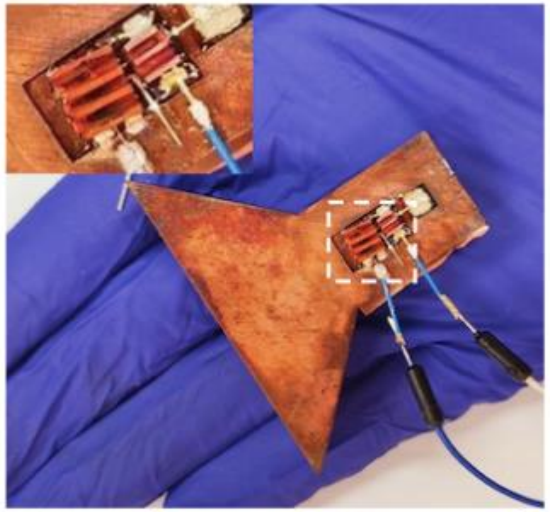


(c)



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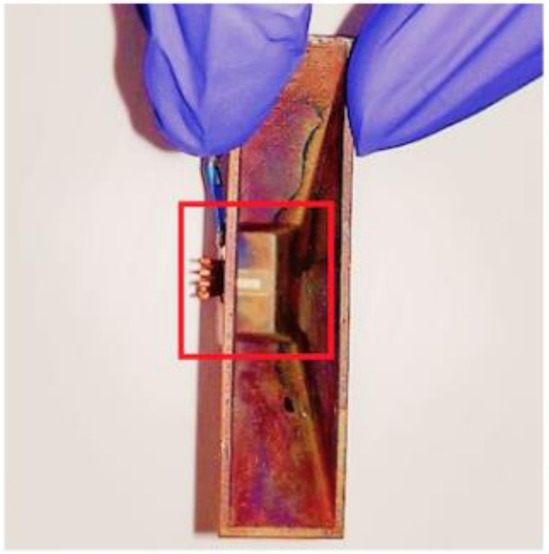
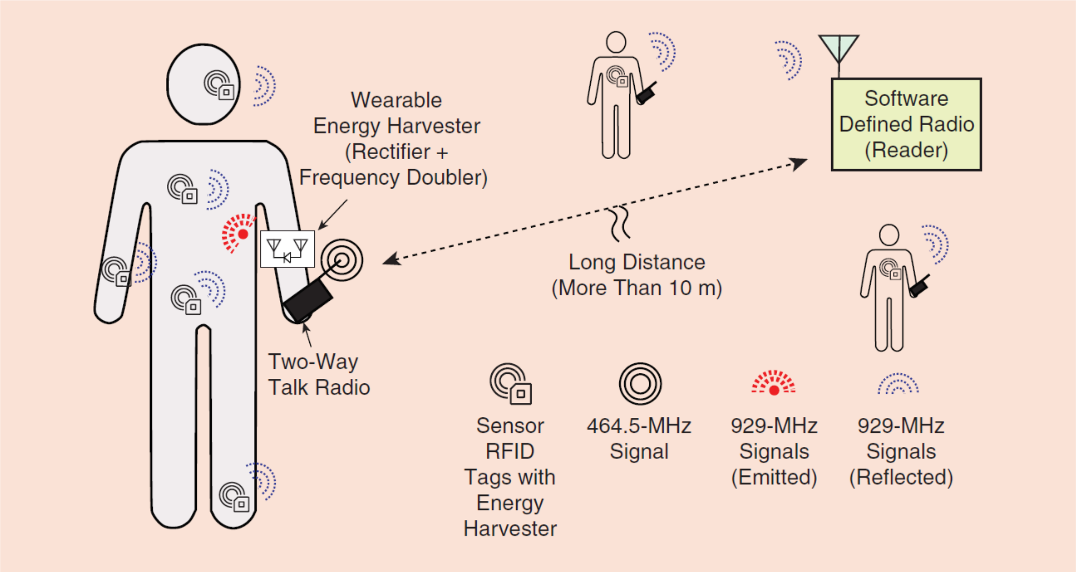
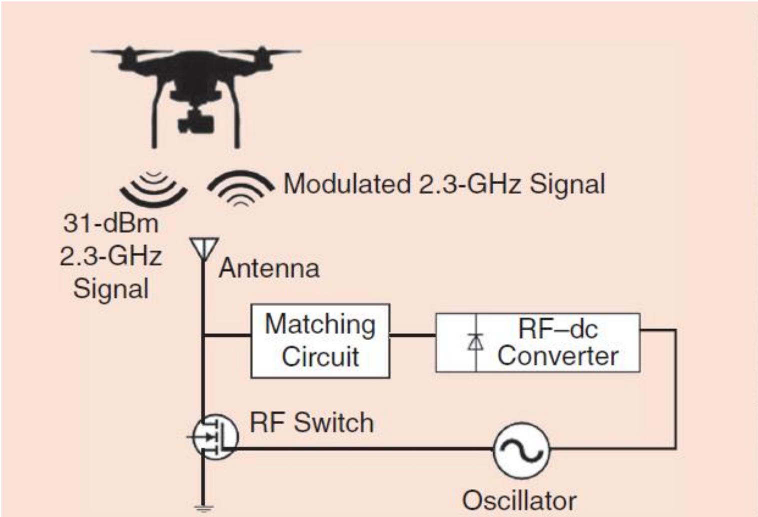
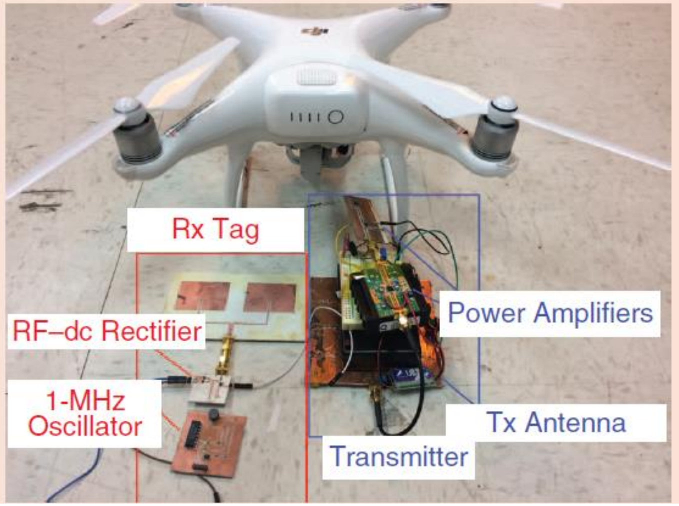
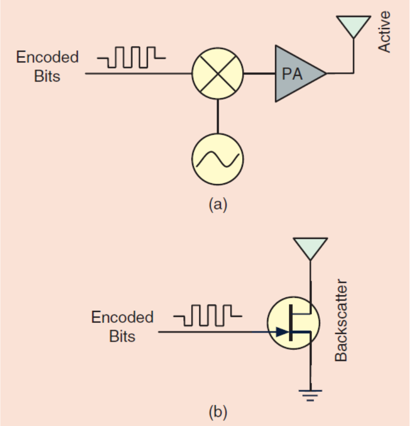


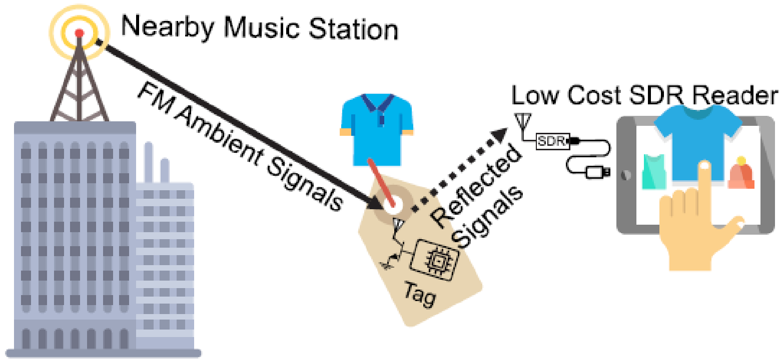
Backscattering: A “Zero-Power” Enabling Technology





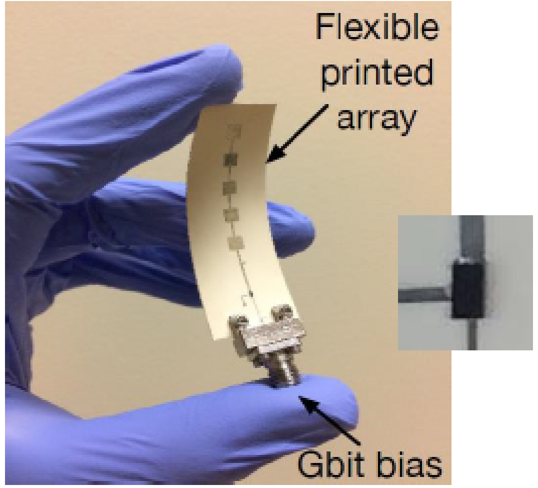


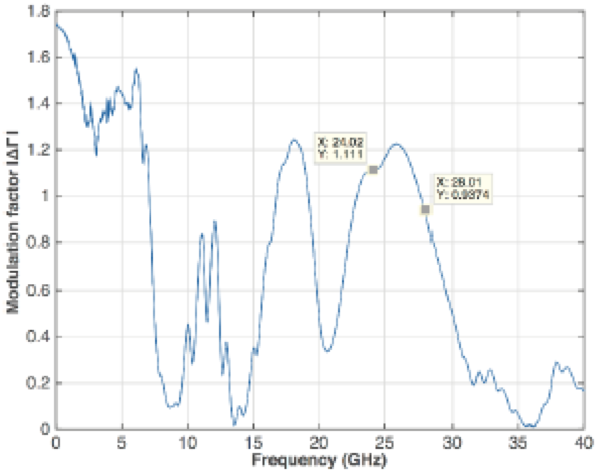




- Gigabit/sec backscattering data rates
- <0.15pJ/bit power efficiencies
- 1km+ interrogation range
- Fully scalable/ultra-low cost

Gbps Millimeter-wave Backscatter

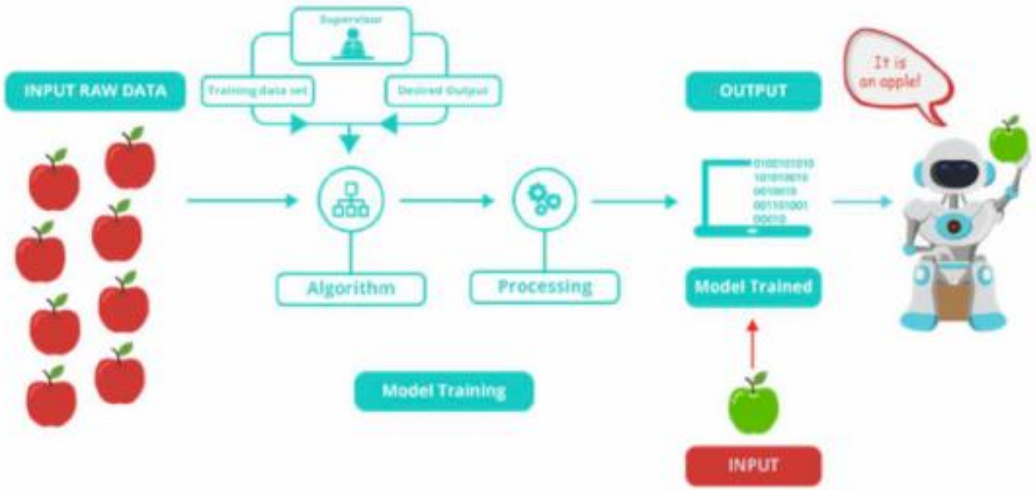




- Printed **flexible** 24-28 GHz tag
- Ultra low-loss substrate
- **First time reported Gigabit** backscatter data rates (> 4 Gbps)
- Extreme energy efficiency < 0.15 pJ/bit
- **3-4 orders of magnitude** beyond current RFIDs

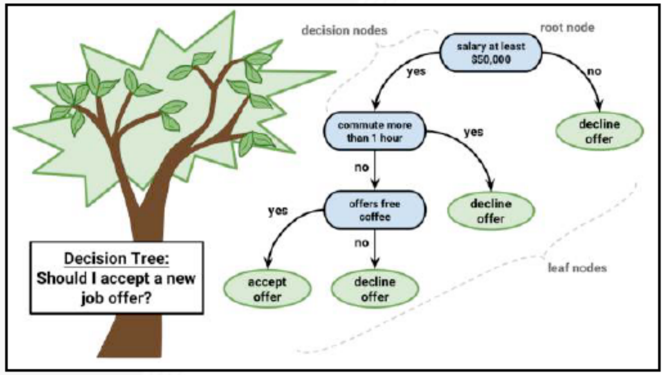
J. Kimionis and M.M. Tentzeris, "Millimeter-wave Backscatter: A Quantum Leap for Gigabit Commu- nication, RF Sensing, and Wearables," in IEEE MTT-S International Microwave Symposium (IMS) 2017, Honolulu, HI, USA, Jun. 2017.

Artificial Intelligence: the key enabler



Decision Trees / k-Nearest Neighbor

- DT
  - Widely used method based on the form of a tree structure
  - Suitable for a non-parametric model with no assumptions
- k-NN
  - Simple instance-based learning for prospective statistical classification
  - For input variables, Euclidean distance is used



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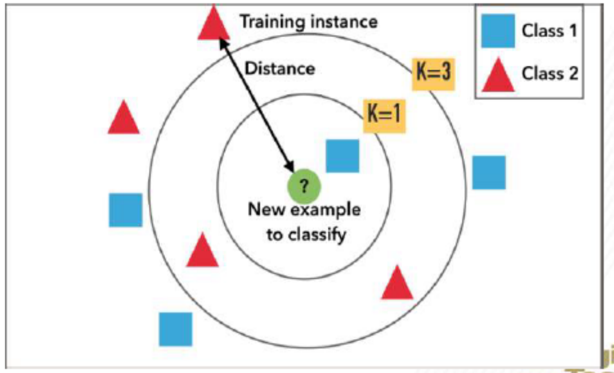

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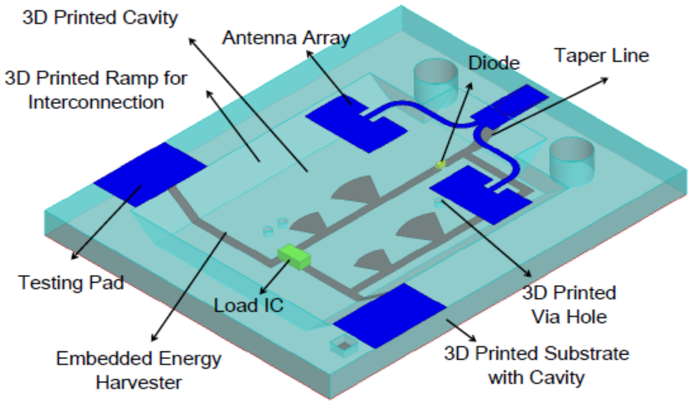
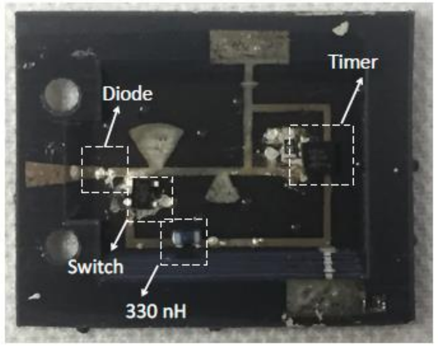
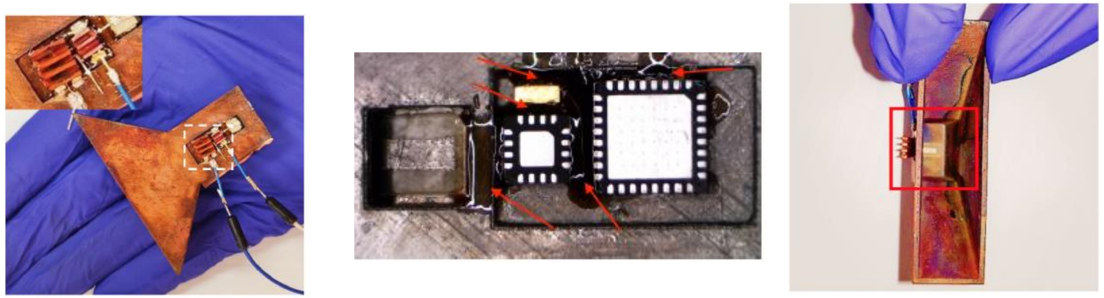
The First Fully Printed Autonomous Wireless Modules (IoT/5G)

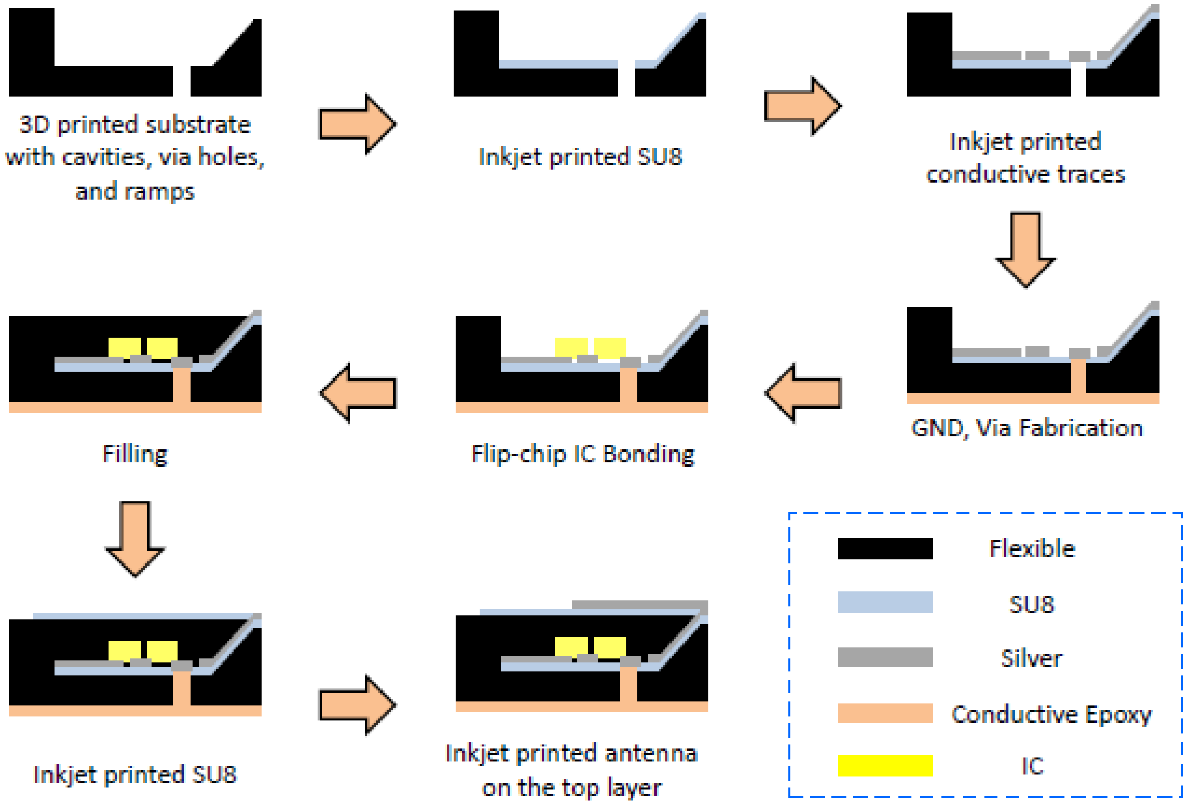




28GHz Backscatter RFID-enabled Sensing 5G/IoT module



12-18 GHz Tunable System-on-Antenna for IoT



T.-H.Lin, S.N.Daskalakis, A.Georgiadis and M.M.Tentzeris, "Achieving Fully Autonomous System-on-Package Designs: An Embedded-on-Package 5G Energy Harvester within 3D Printed Multilayer Flexible Packaging Structures", Proc. of the **2019 IEEE IMS Symposium,** Boston, MA, June 2019, pp.1375-1378.

Additively Manufactured mm-Wave Multichip Modules with Fully Printed “Smart” Encapsulation Structures [16]

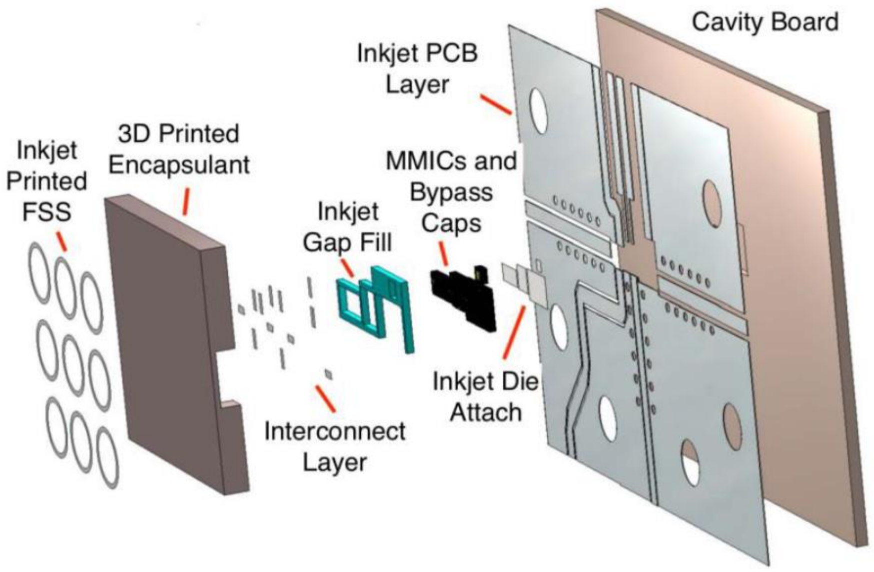
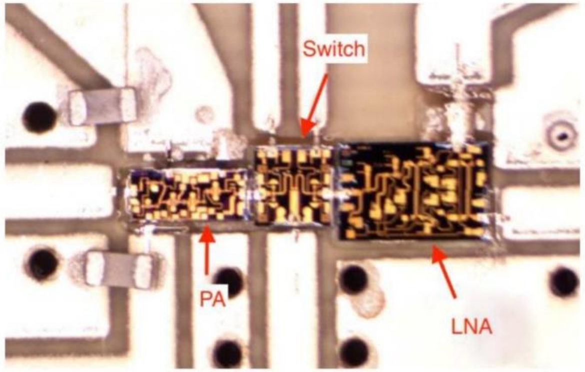
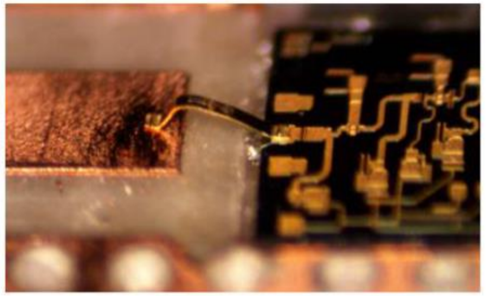
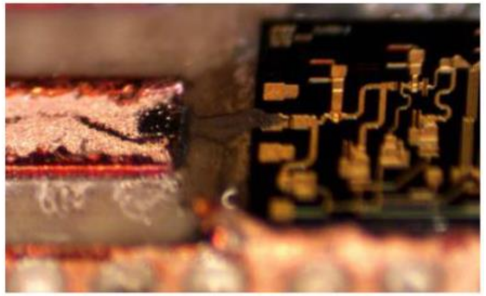


Fig. 2. Exploded view of the complete encapsulated RF front-end MCM, showing the multiple layers that were additively manufactured.



- The first mm-wave multi-chip module (MCM) with on-demand “smart” encapsulation.
- Fabricated using inkjet printing and 3D printing.
- Inkjet printed interconnects exhibited a superior |S21| performance through out the whole operation range up to 40GHz with a peak of 3.3dB better gain for a Ka-band LNA.
- The proof-of-concept front-end MCM demonstrates exceptional performance





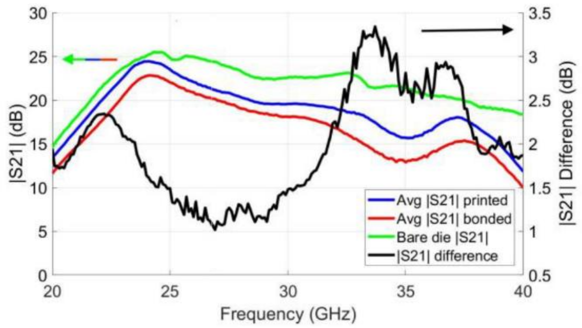


Fig. 9. Left axis: average insertion loss for printed and bonded samples. Right axis: difference in insertion loss between the printed and bonded samples (printed minus bonded). The bare die (without interconnects or evaluation board) measurement is shown in green as a reference.

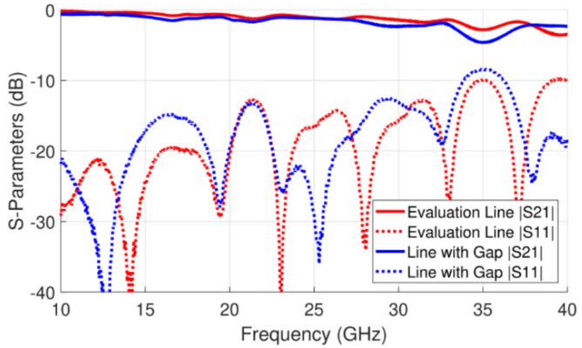
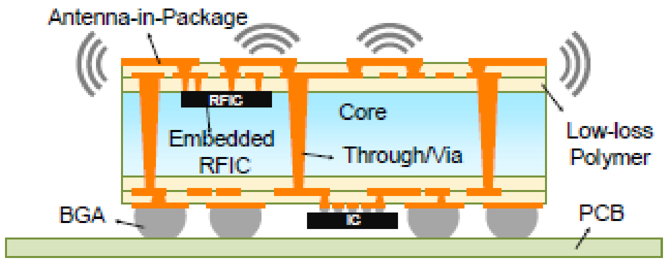


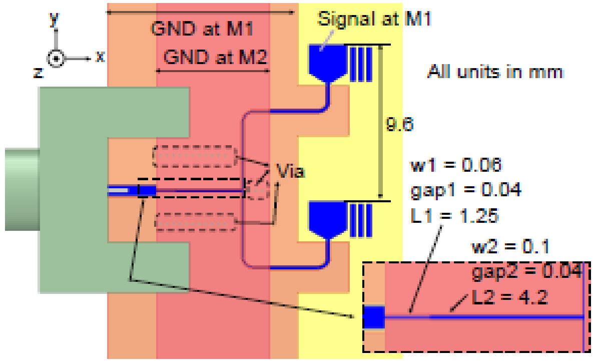
Fig. 6. |S11| and |S21| comparison between a regular thru transmission line and interconnected transmission line structures using inkjet printing techniques.

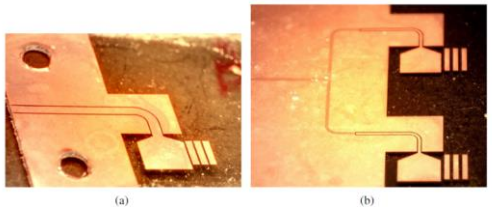
5G Broadband and Miniaturized Antenna-in-Package

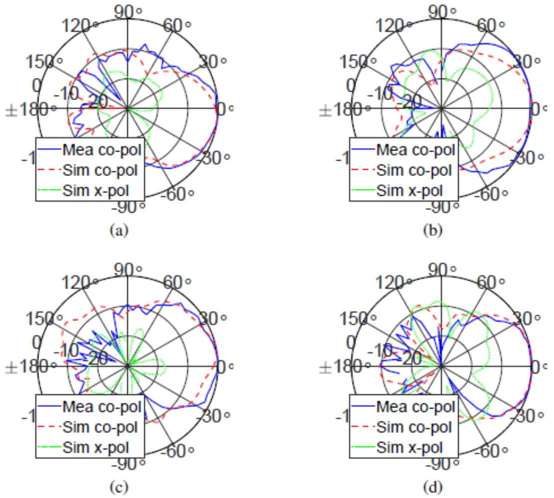
3D and inkjet printed SoP Design



AiP design details

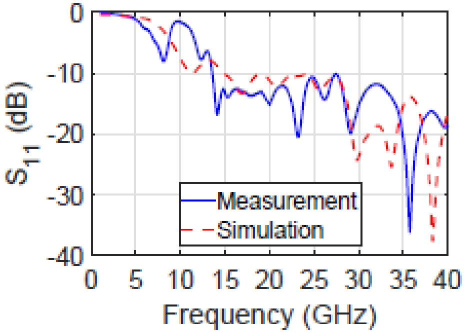


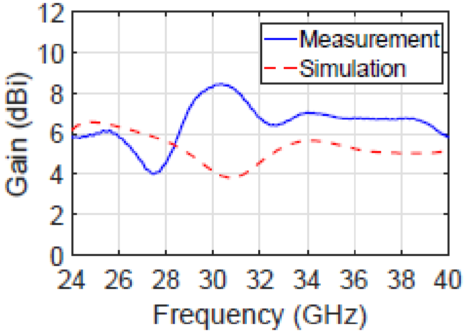




Measured and simulated normalized radiation patterns for Yagi AiP element design at (a) 24.25 GHz E-plane, (b) 24.25 GHz H-plane, (c) 40 GHz E-plane, and (d) 40 GHz H-plane.

- Fully additive manufacturing (3D and inkjet printing)
- Broadband 5G package-integrated antenna
- Flexible materials for resistance to shocks and vibrations
- First to Cover 24.25 GHz – 40 GHz (FBW: 49%)
  Realized gain > 4 dBi
  $0.25\lambda o \times 0.45\lambda o$ element size



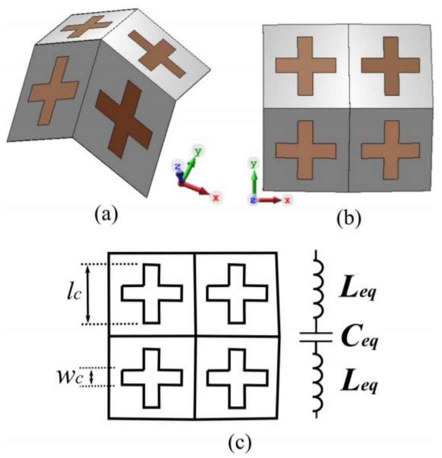


T.-H.Lin, K.Kanno, A.O.Watanabe, P.M.Raj, R.R.Tummala, M.Swaminathan and M.M.Tentzeris, "Broadband and Miniaturized Antenna-in-Package (AiP) Design for 5G Applications", IEEE Antennas and Wireless Propagation Letters, Vol.19, No.11, pp.1963-1967, November 2020.

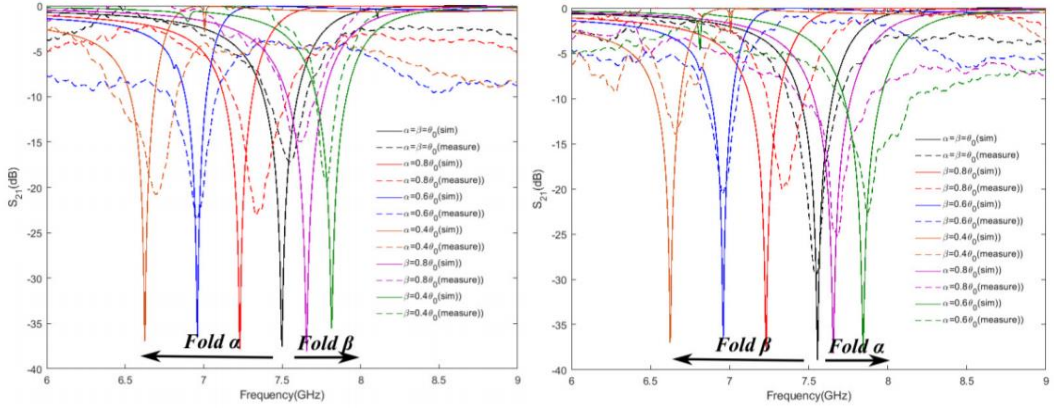
Origami-inspired FSS Using Eggbox Structure

Key Features

- "Eggbox" element with two tunable directions
- Cross-shaped conductive pattern with two polarizations
- Much wider tunable range than Miura-based FSS



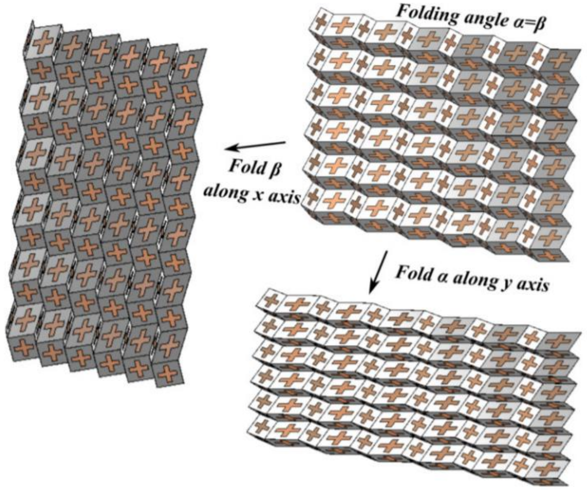
Design of cross-dipole eggbox FSS element: (a) perspective view; (b) top view; (c) equivalent circuit.



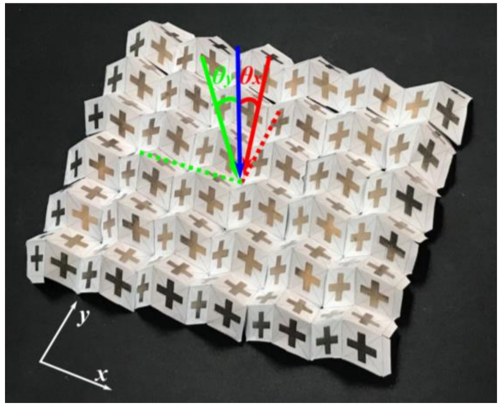
Simulated and measured S21 of horizontal and vertical polarizations with different folding angles.

	Type	Pattern	Freq Tunable Range	Polarization
	Miura	Dipole	12.8%	Linear
	Miura	Dipole	13.5%	Linear
	Miura	Cross	19%	Dual-linear
(this work)	Eggbox	Cross	25%	Dual-linear 4-DOF-tunable

Performance comparison of different configurations.



Two tunable directions of eggbox FSS

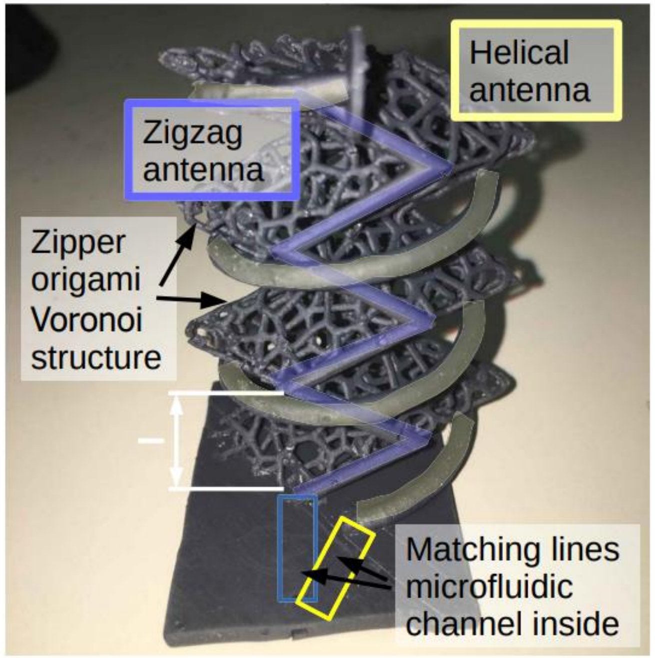


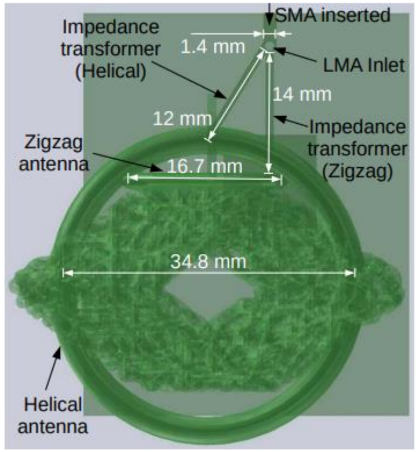
Fabricated prototype

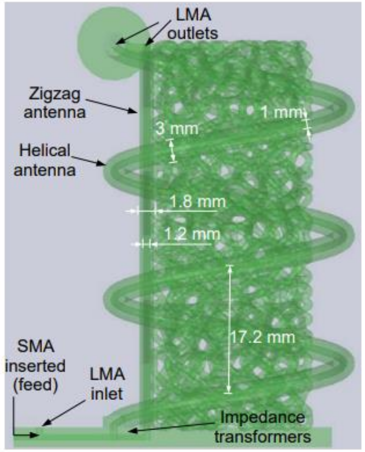
Y.Cui, R.Bahr, S.Van Rijs and M.M.Tentzeris, "A Novel 4-DOF wide-range tunable frequency selective surface using an origami "eggbox" structure", International Journal of Microwave and Wireless Technologies, Vol.13, No.7, pp.727-733, September 2021.

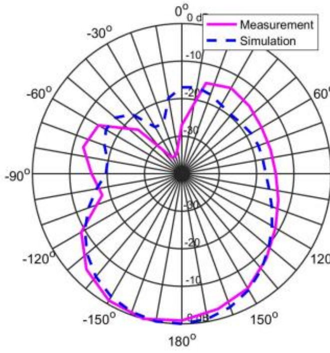
3D printed Liquid-metal-alloy microfluidics-based Origami Zigzag and Helical Antennas “Trees”

- “Tree” (zigzag/helical antenna) with dual-band (3GHz/5GHz) operability and different polarizations (linear/circular).
- Varying radiation patterns with “tree” compression.

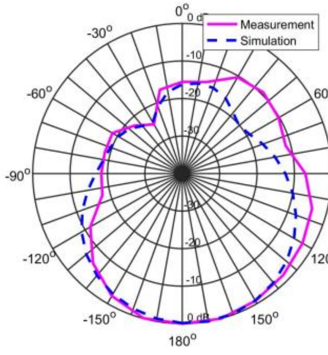




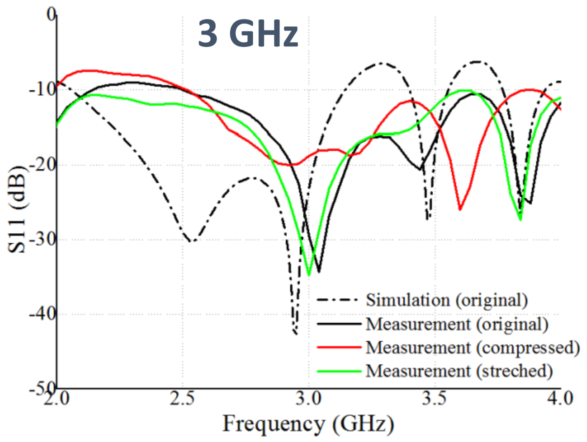


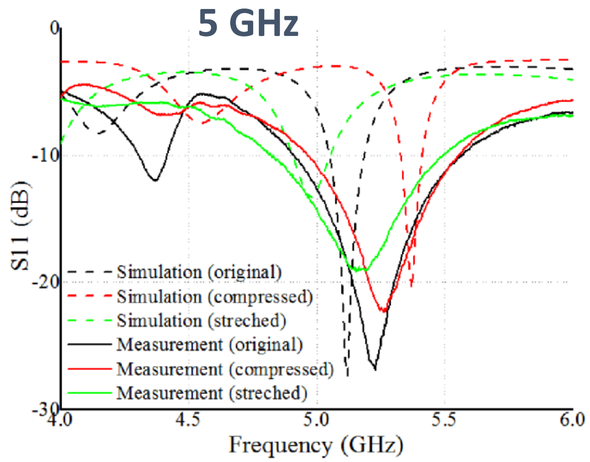


Original (5 GHz)



Compressed (5 GHz)



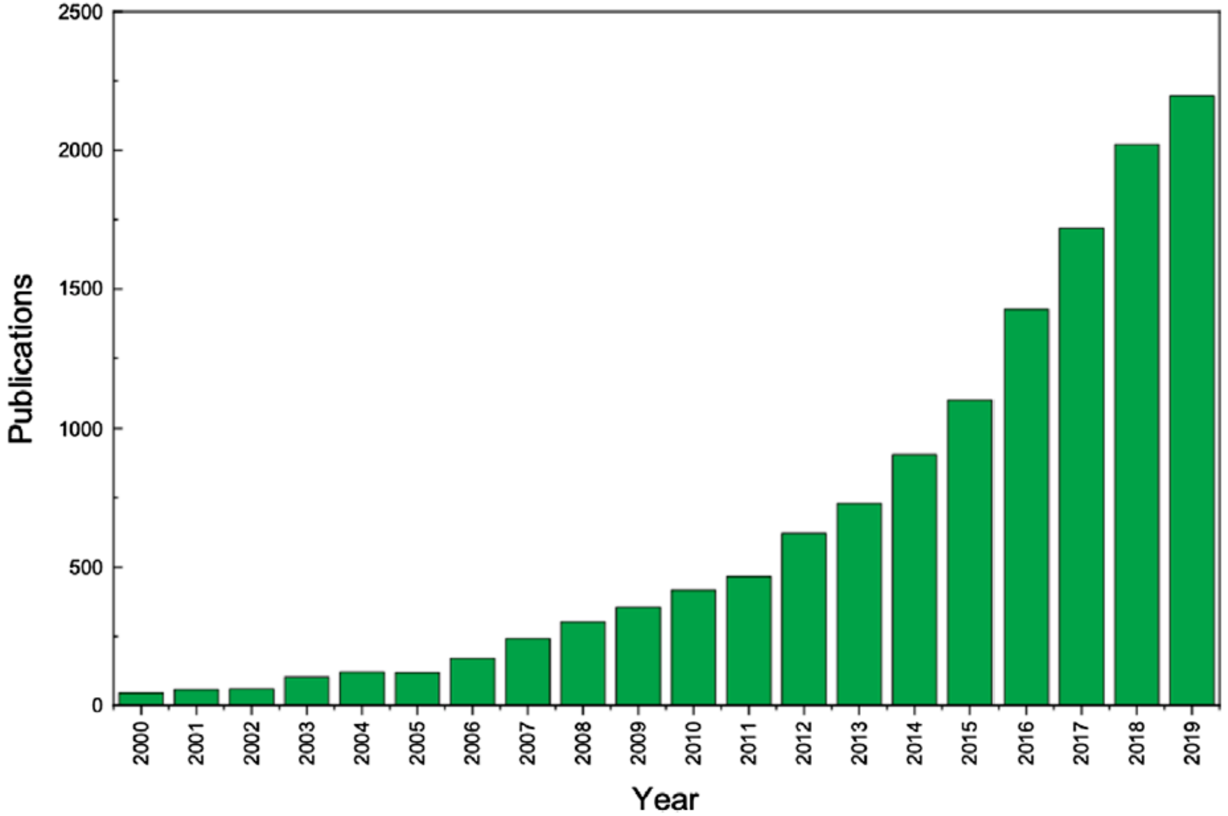


Su, W., Nauroze, S. A., Ryan, B., & Tentzeris, M. M. (2017, June). Novel 3D printed liquid-metal-alloy microfluidics-based zigzag and helical antennas for origami reconfigurable antenna “trees”. In 2017 IEEE MTT-S International Microwave Symposium (IMS) (pp. 1579-1582).

Printed Flexible Electronics

Increasing demand for flexible electronics for:

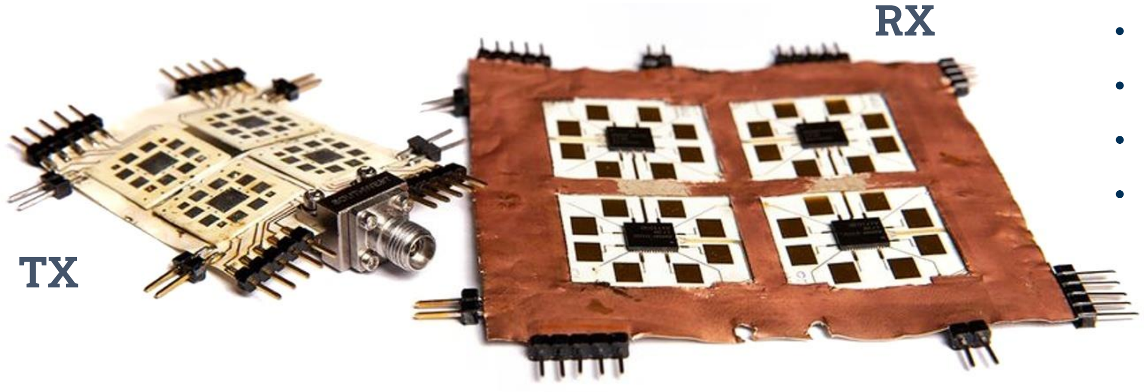
1. Wearables.
2. Textile electronics.
3. Biomonnitoring and sensing.
4. Low-cost applications.
5. Disposable and environmentally friendly.
6. Light weight and conformal sensors for robots and aircrafts.



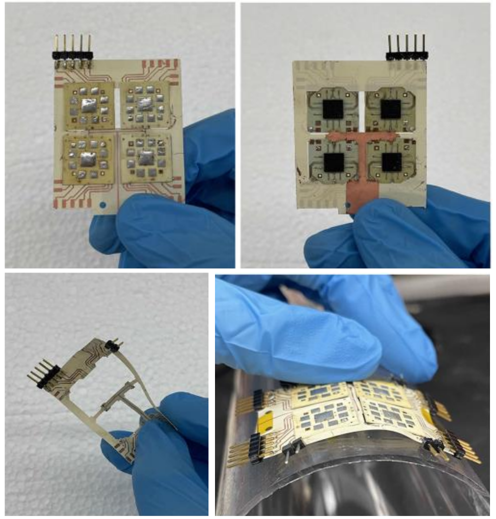
Research publications for the term "**Flexible Electronics**"

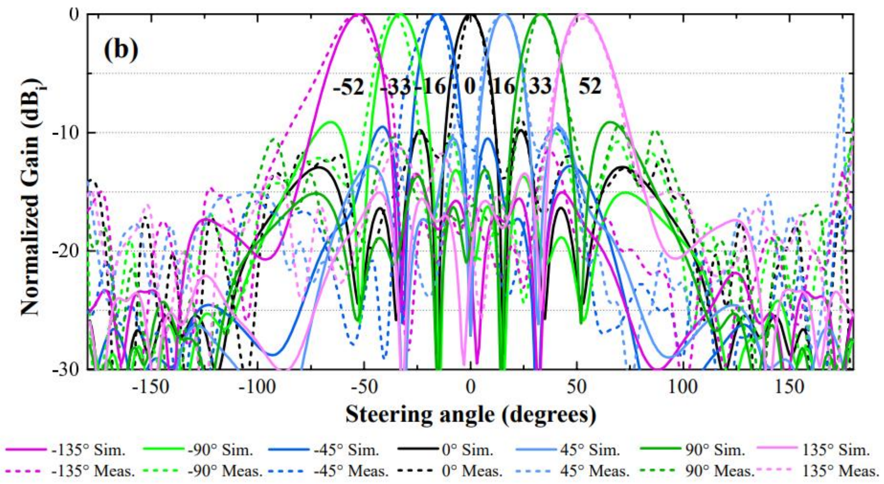
Corzo, et. al. (2020), doi: 10.3389/felec.2020.594003

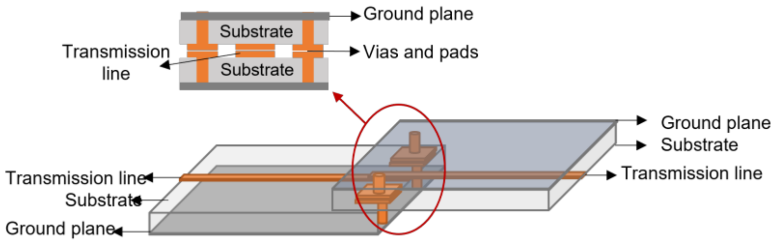
Flexible Tile-Based Phased Array Antennas for 5G Communications



- Tile-based approach suitable for **modular** and **conformal large-array** systems.
- Array tiles are connected using a “flip chip” microstrip-to-microstrip interconnect.
- Wideband transmission with insertion loss less than 0.3dB from 10 GHz to 30 GHz.
- **Key features:**
  - Greater scalability and flexibility.
  - Array to change dimensions based on the application.
  - Conformally wrap array around curved surfaces.

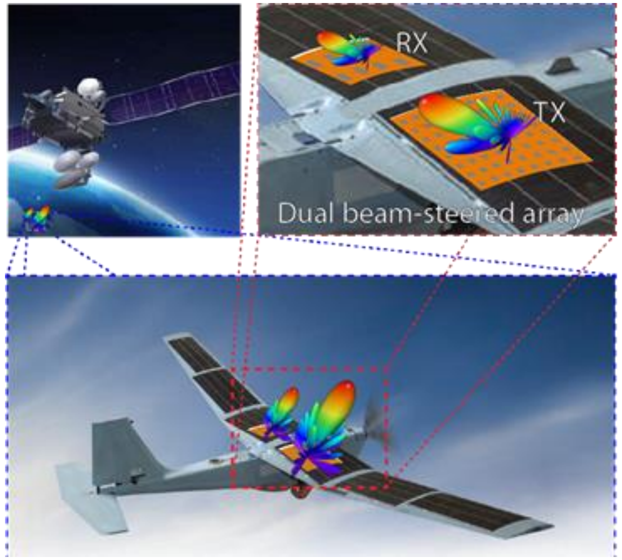


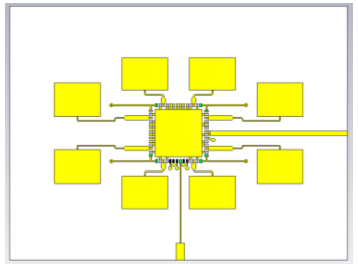




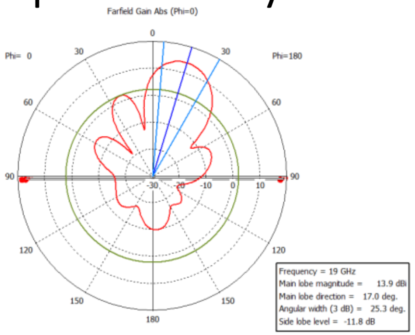
Fully Printable Phased Array Tiles

- Independent **beam-steerable** flexible planar TX and RX antenna array systems
- Frontend ICs with built-in phase shifters to steer the array of each tile, with **individually controlled radiating element**
- Corporate feed network connects **removable tiles** to build a larger array
- **Flexible tiles and feeding network** can be conformally wrapped around curved surface

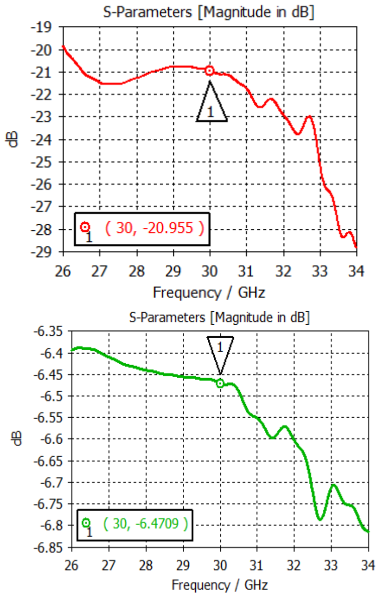




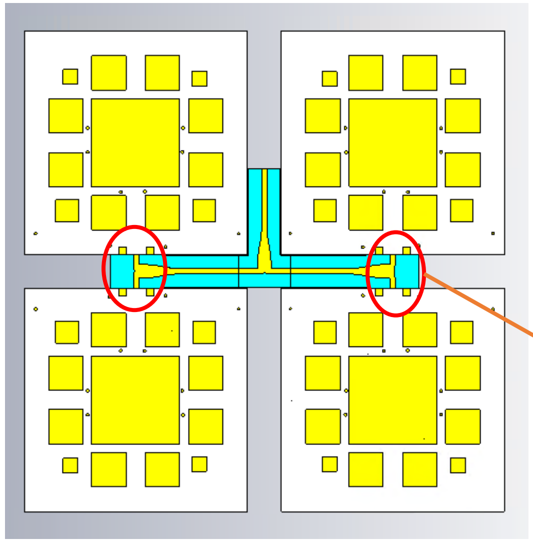
Rx phased array tile



Beam steering

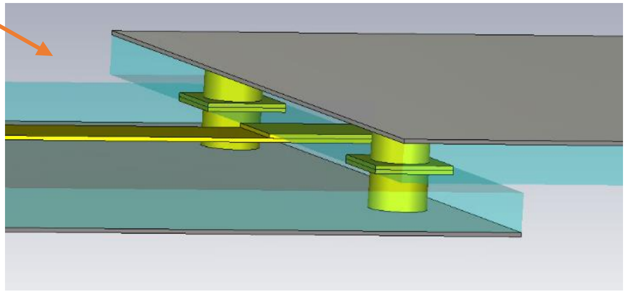


Simulation results of 4 tiles

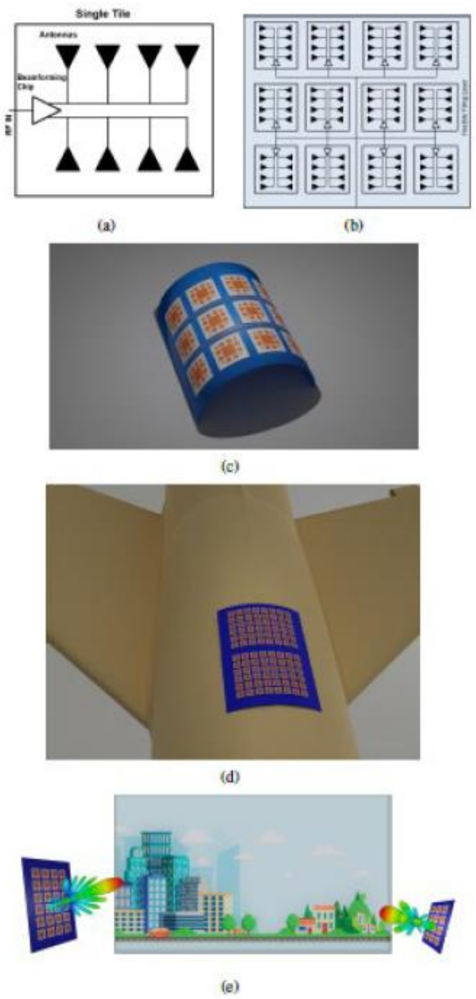


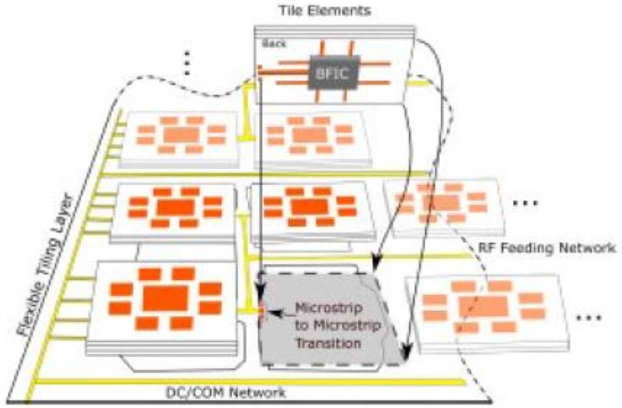
Tx phased array tiles connected by corporate feed

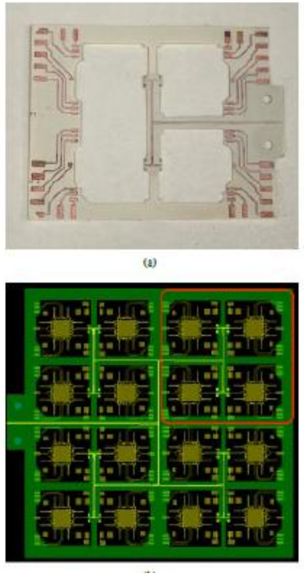
Interconnect of microstrip-to-microstrip transition

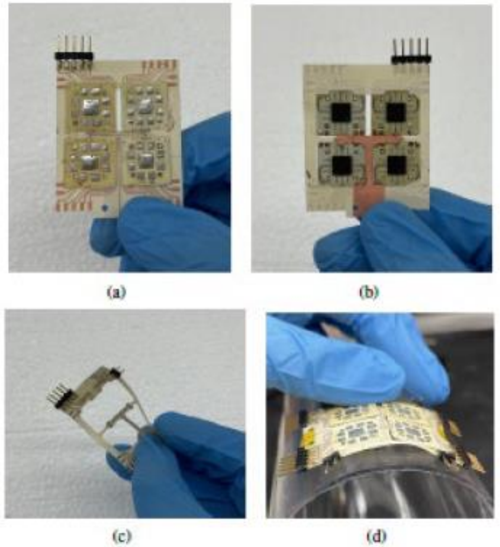


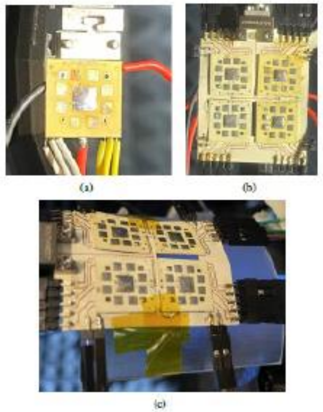
Tile-by-Tile Reconfigurable Intelligent Surfaces





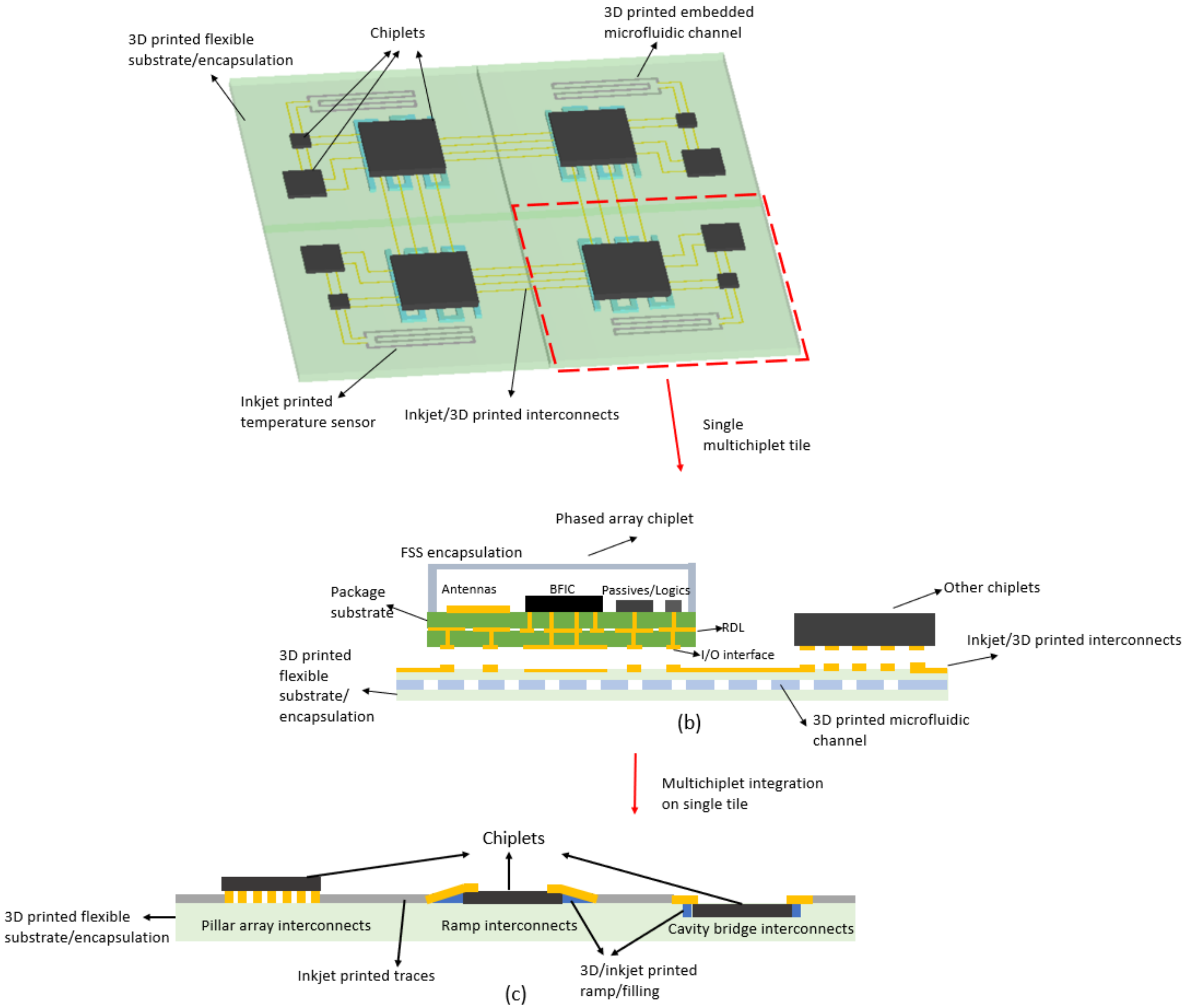




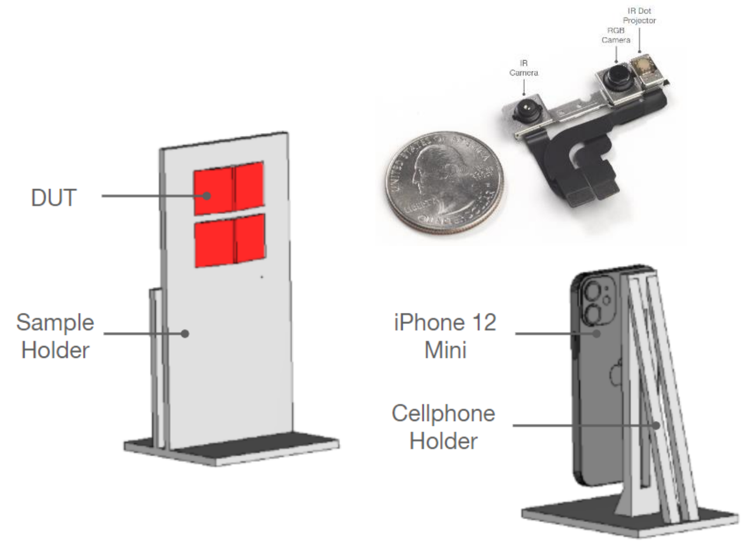


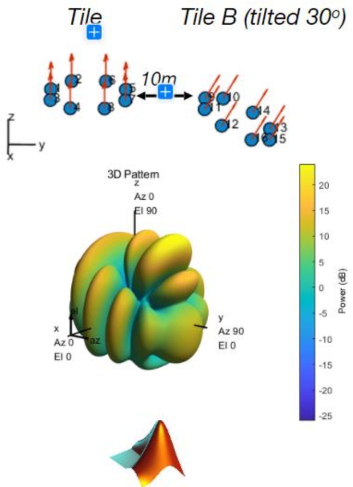
Chiplet-Based B5G Topologies

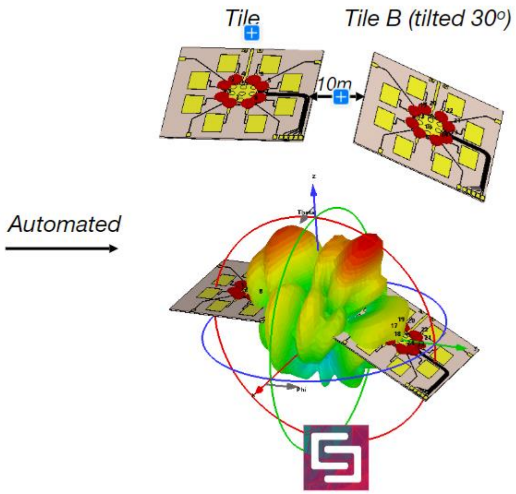
- Fully printed next generation chiplet based phased array SoP designs with flexible packaging structures ("packaged tiles"), that enable massively scalable high-performance 5G+/6G/sub-THz flexible integrated wireless modules.
- 3D printed die-to-die and die-to-package interconnection topologies that can enable robust fan in/fan out (50-100+) interconnects with 10x 15x smaller losses and parasitics compared with conventional wire-bonding and vias up to 70GHz+ frequencies.
- Integration of microfluidic systems, EMI/EMC suppression structures and self-monitoring sensors in fully additively manufactured encapsulations.
- Optimized hybrid additive manufacturing technique with submicron printing capability and 3D printed heat-resistant (200C+) and "green" biodegradable materials demonstrating very significant benefits for future customized and scalable flexible systems operating up to sub-THz frequency range.
- Demonstration of fully printed conformal and reconfigurable chiplet based phased arrays for 6G/sub-THz flexible systems enabling wide-angle scanning even for extreme radii of curvature.
- Inkjet/3D printed interconnects with excellent electrical and mechanica reliability over monotonic, cyclic bending tests (<0.1dB/mm insertion loss during 10000+ bending cycles over <1 inch bending radius).

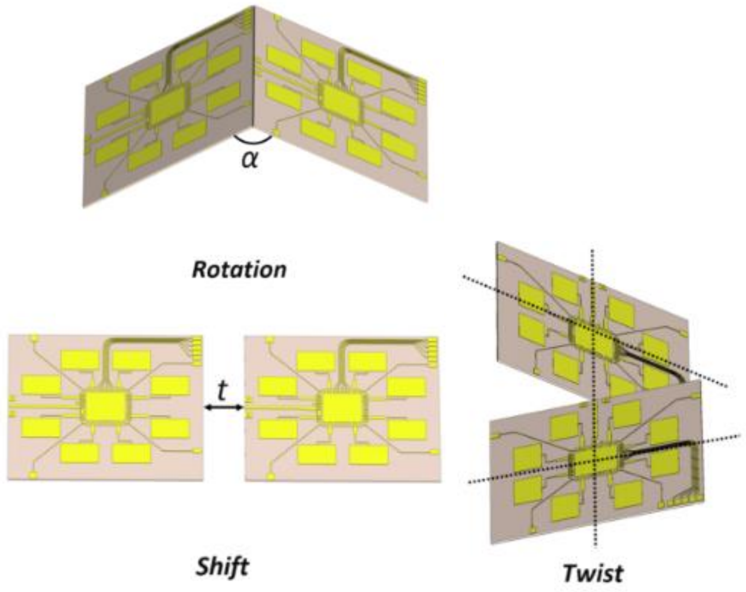


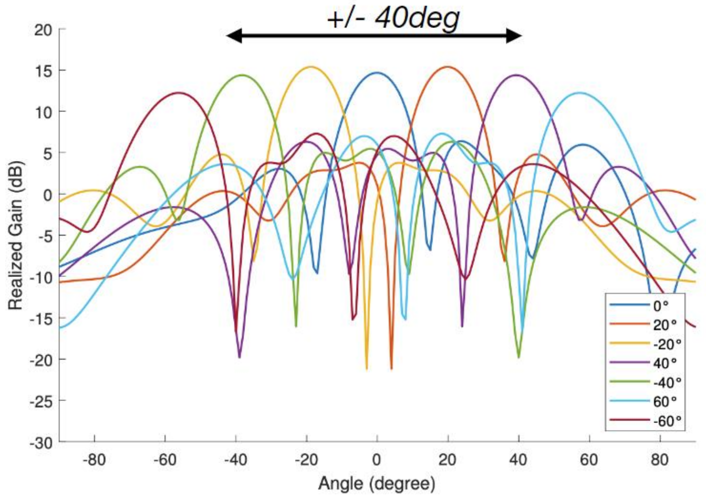
Computer Vision Aided Calibration of Foldable PCB Topologies

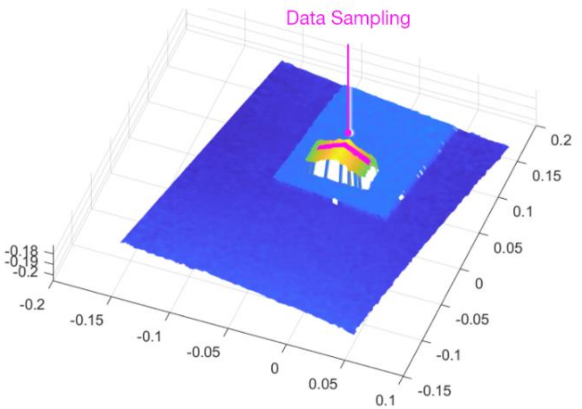


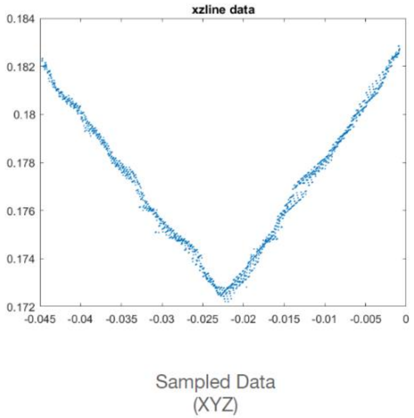


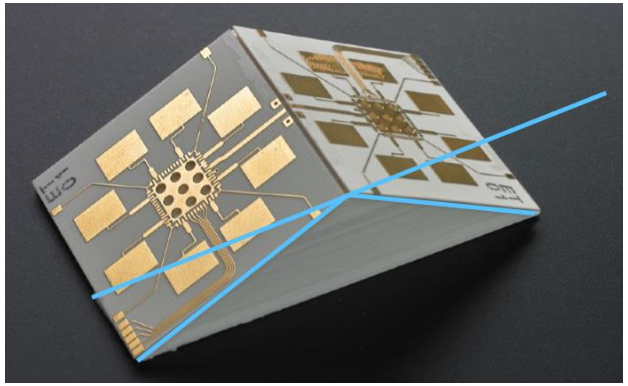








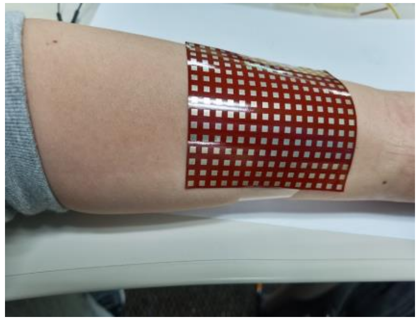


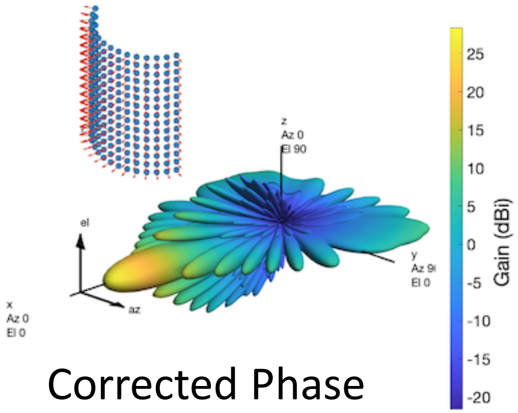


Self-Calibrated "Flex-compensating" Flexible Arrays

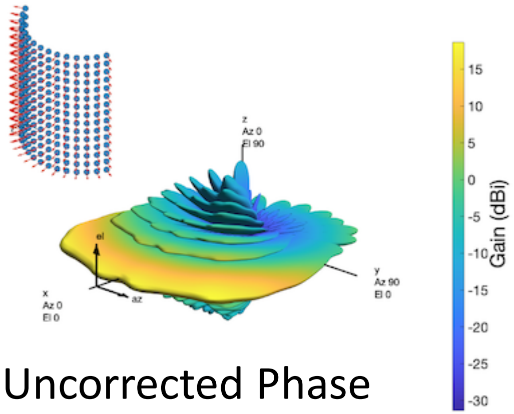
- Conformal applications of arrays allows for superior integration in wearables, aerospace and communication platforms.
- However, phase error causes gain degradation -> Needs Correcting

Requires a way to adaptively know the current bending condition in order to accurately correct for bending





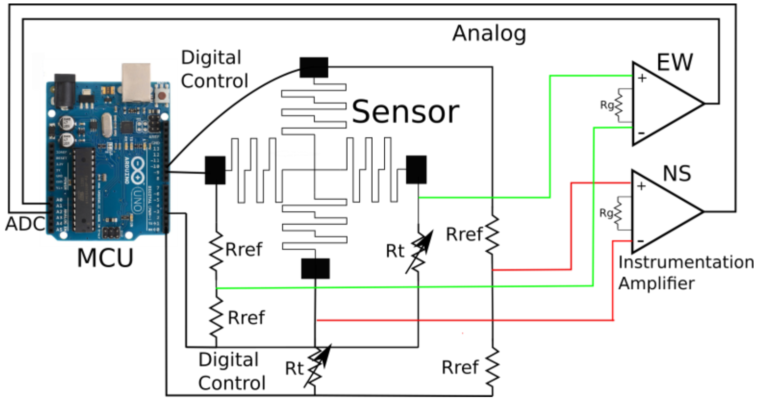
Corrected Phase

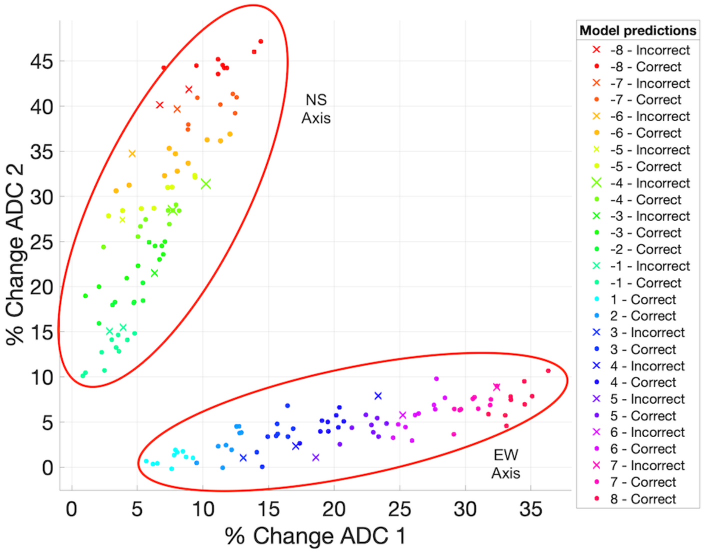


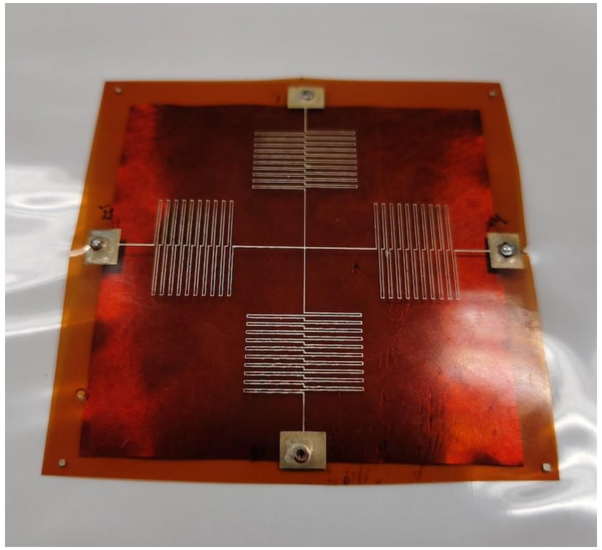
Uncorrected Phase

Self-Calibrated "Flex-compensating" Flexible Arrays

- Utilize inkjet printed resistance sensors -> Resistivity changes with bending
- Classification algorithm: Linear Discriminant Analysis to classify bend radius and orientation ON THE FLY
  - Using LDA: 90% accuracy and only 0.071dB in gain error







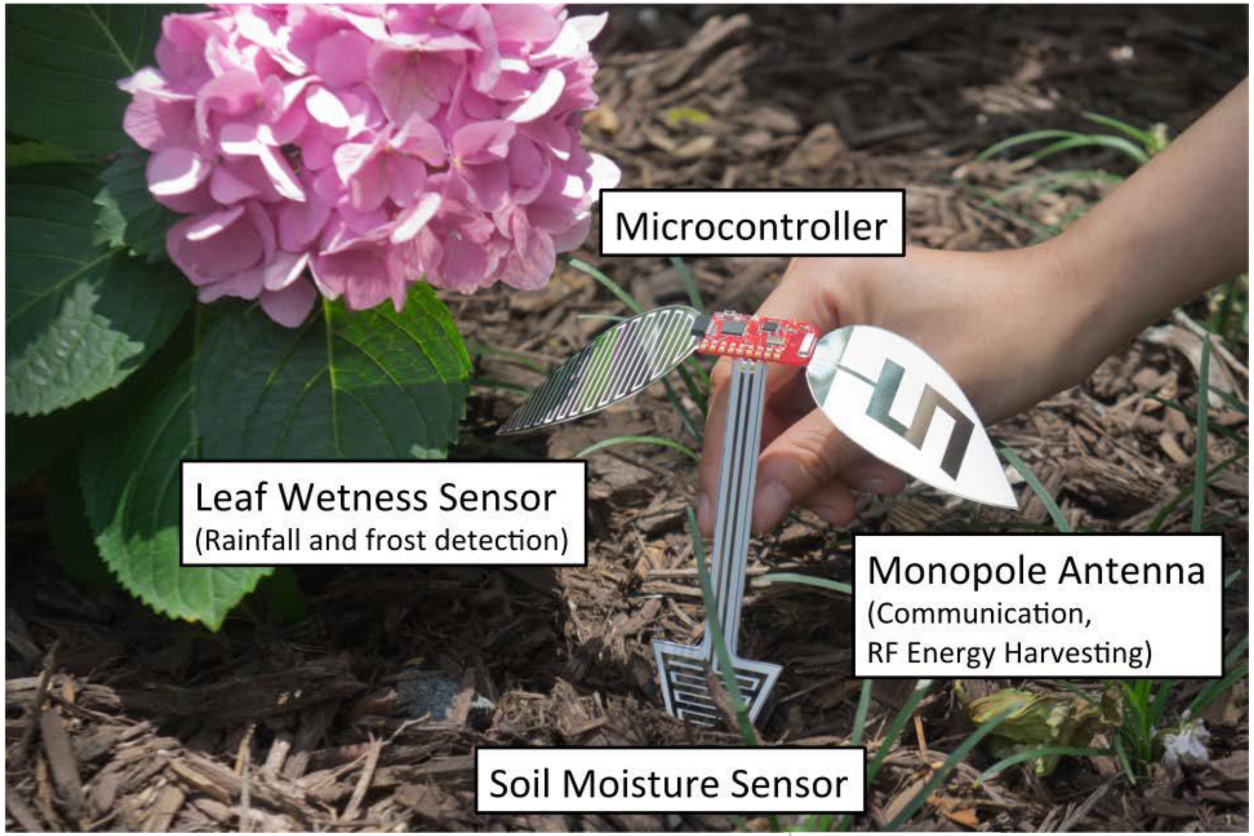
Inkjet-Printed Soil Moisture and Leaf Wetness Sensor

Features:

Inkjet-printed capacitive sensor for soil moisture and rain detection

Applications:

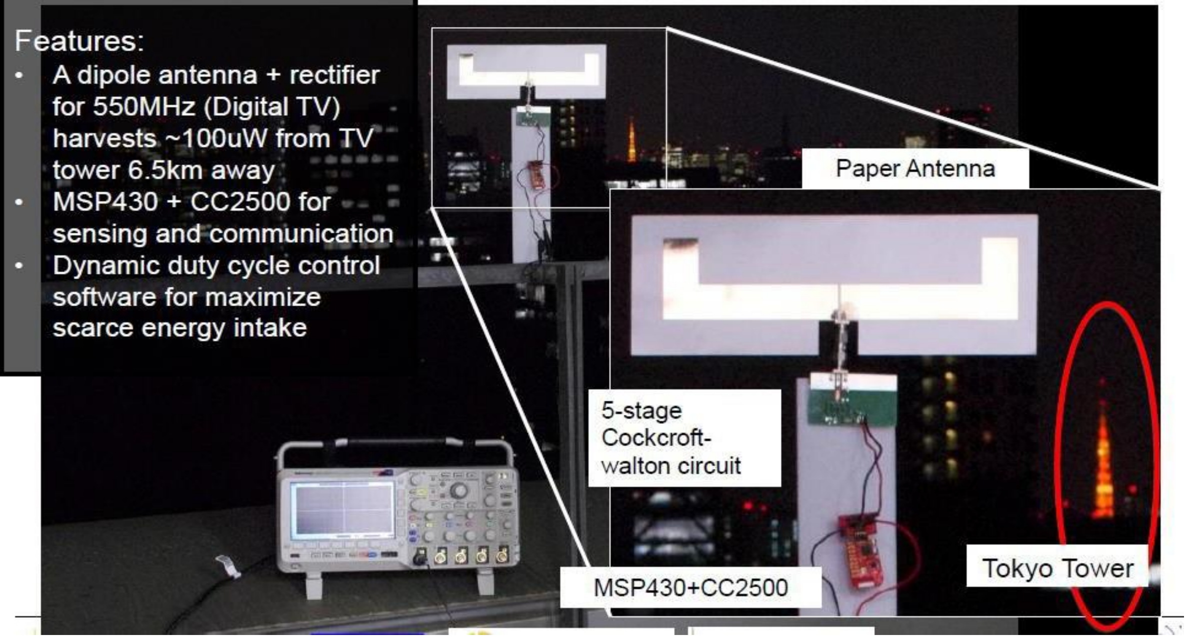
Irregation optimization, quality control of high-value fruit, and land-slide detection in mountains

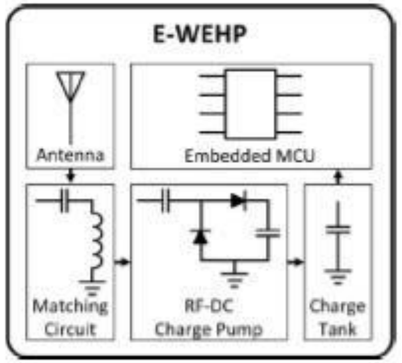


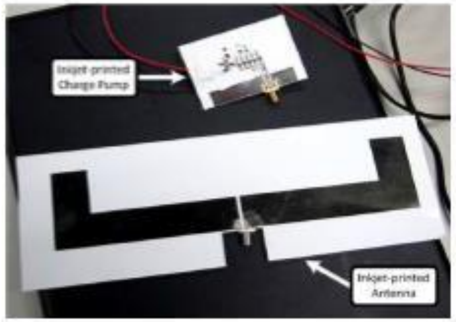
NEDO 東京大学 THE UNIVERSITY OF TOKYO Georgia Institute of Technology

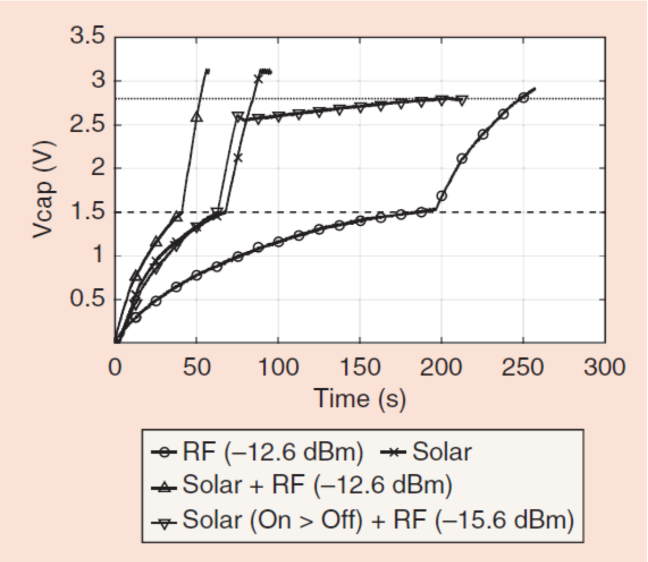
Energy from Thin Air? “Agnostic” Ambient Multiform Energy Harvesting

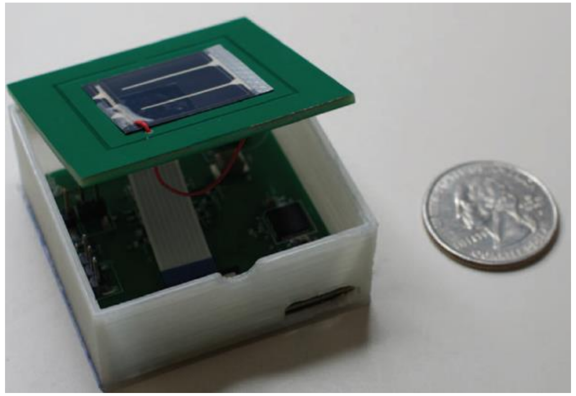
Features:
- A dipole antenna + rectifier for 550MHz (Digital TV) harvests ~100uW from TV tower 6.5km away
- MSP430 + CC2500 for sensing and communication
- Dynamic duty cycle control software for maximize scarce energy intake

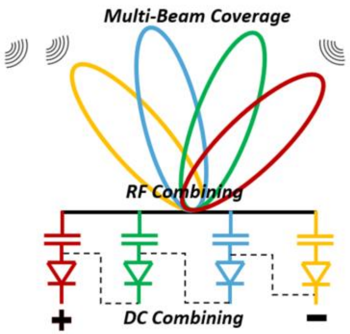


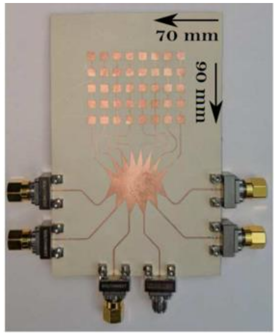


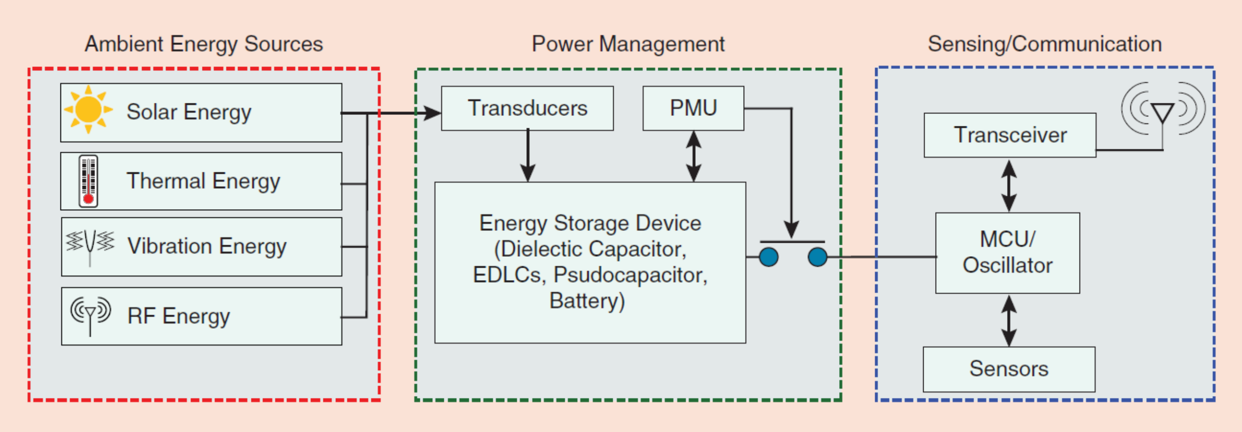








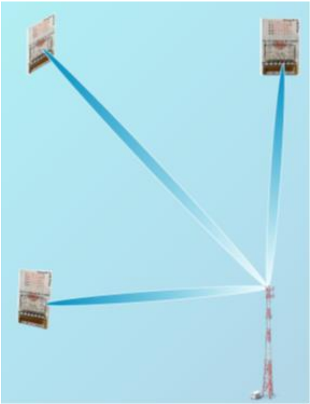


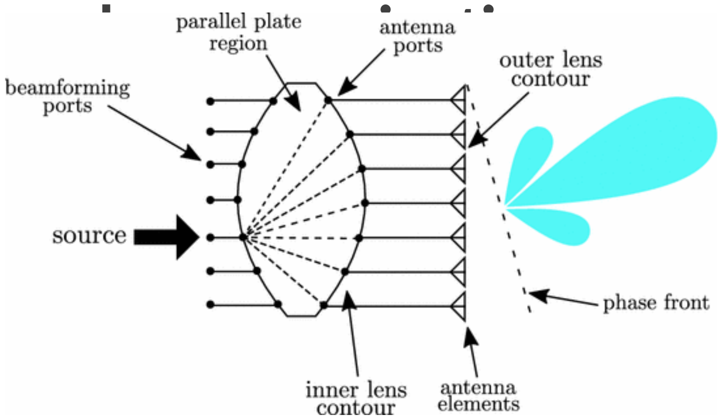


Wireless Charging Metasurfaces
Using 5G/B5G As A Wireless Power Grid (I)

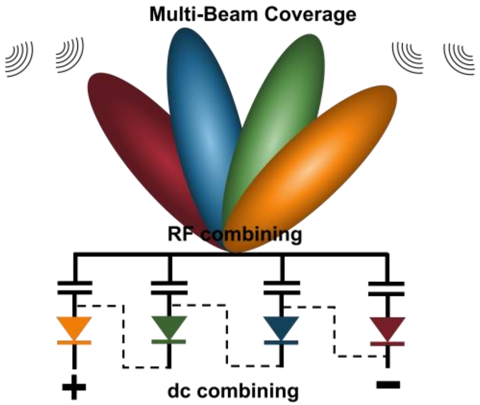
Rotman Lens for mm-wave harvesting

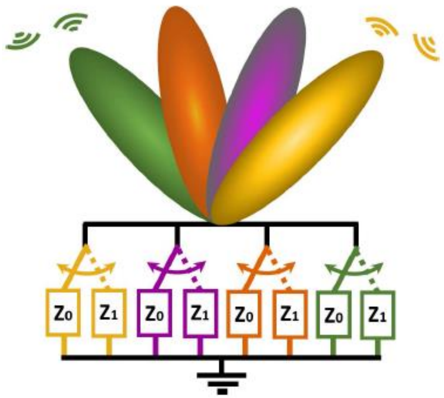
Breaking the High Gain and Large Beamwidth Trade-off at mm-Wave Frequencies and addressing the most conventional implementation disadvantages:





- Electrically large antennas
- High gain and lack of isotropic behavior
- Need for Use of Beamforming networks (**BFNs**)





A.Eid, J.G.D.Hester and M.M.Tentzeris, ``5G as a Wireless Power Grid," **Nature** Scientific Reports, No.11:636, January 2021.

Wireless Charging of Wireless Sensor Modules Using 5G

How does it work

Dual Combination: RF + DC

Scavenge mm-Wave Signals

STEP 01

Antenna arrays connected to the antenna ports of the Rotman lens scavenge the mm-wave energy from all directions.

RF Combine and Focus

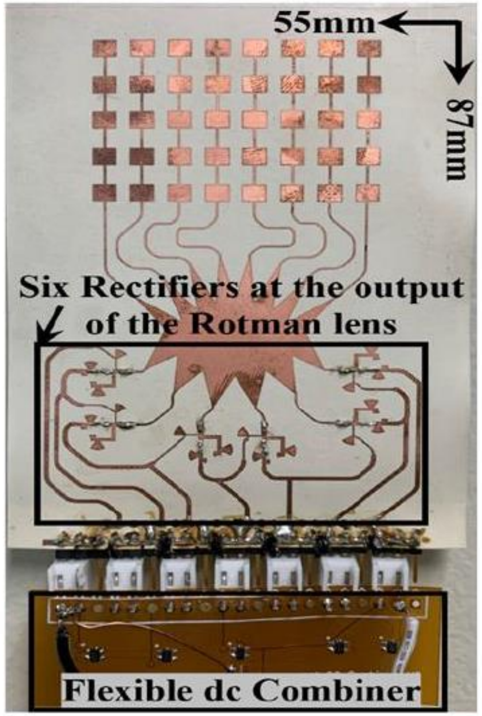
STEP 02

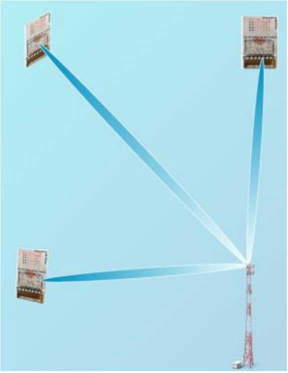
The Rotman lens combines internally all the mm-wave signals collected by the antennas and focuses them to one beam port on the opposite side, where a rectifier is connected.

Rectify and DC Combine

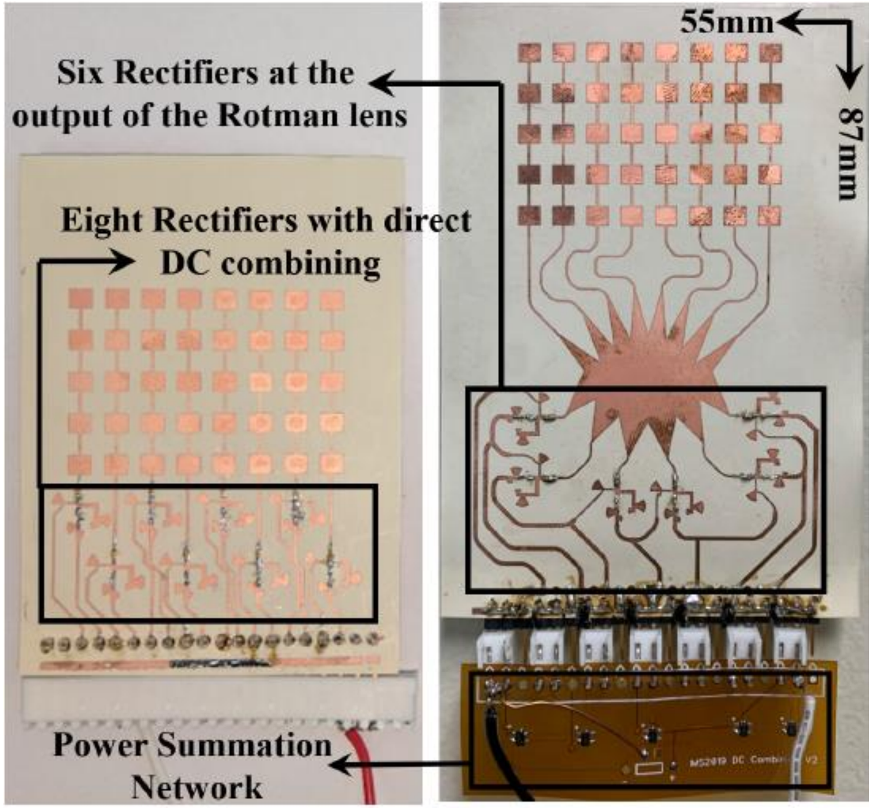
STEP 03

The rectifiers connected at the beam ports of the Rotman lens convert the mm-wave energy to DC power. The DC combiner enables an efficient voltage extraction irrespective of the direction of the incoming signal.

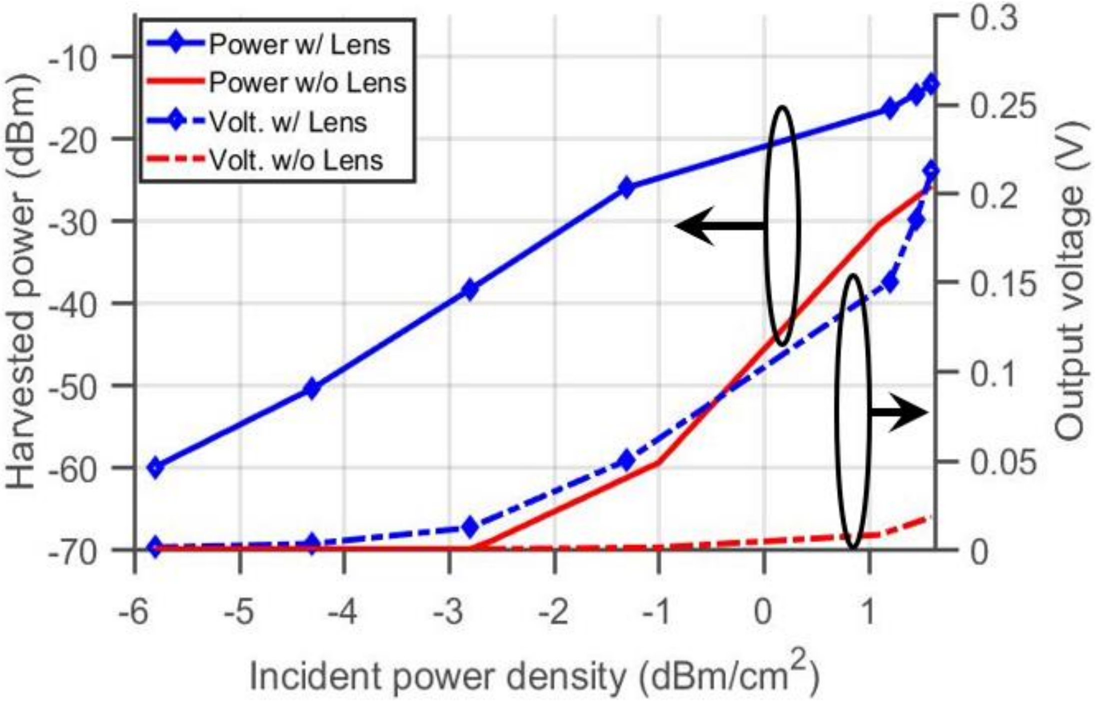




Comparison of this “Direction Agnostic” Solution vs. a Standard Array

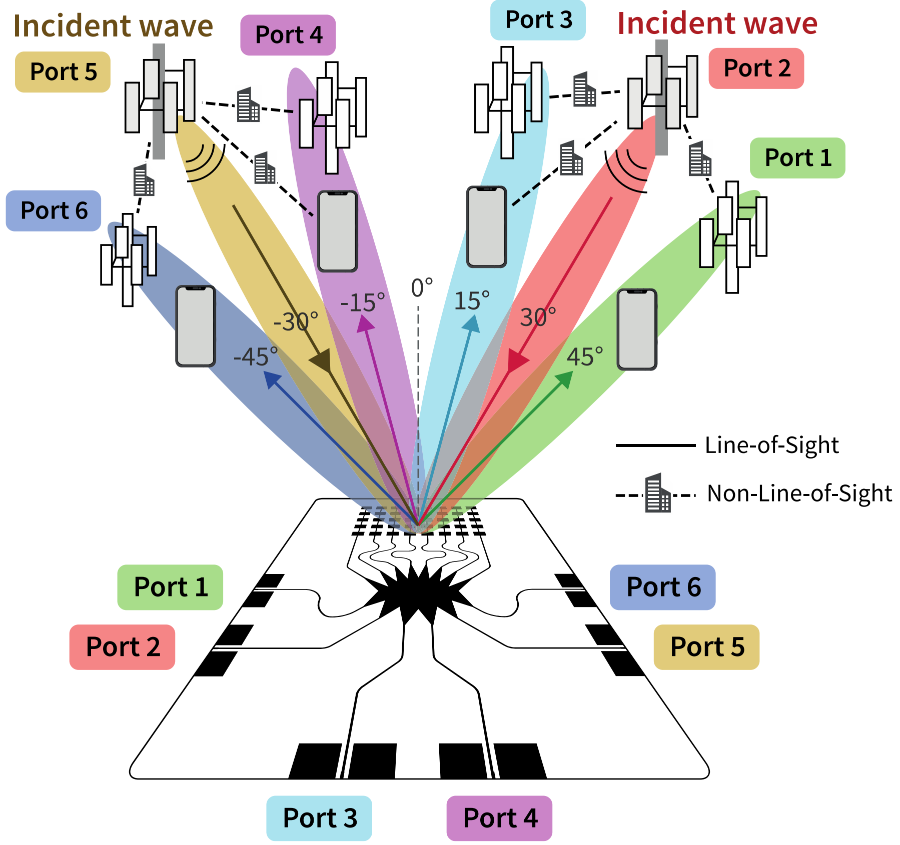


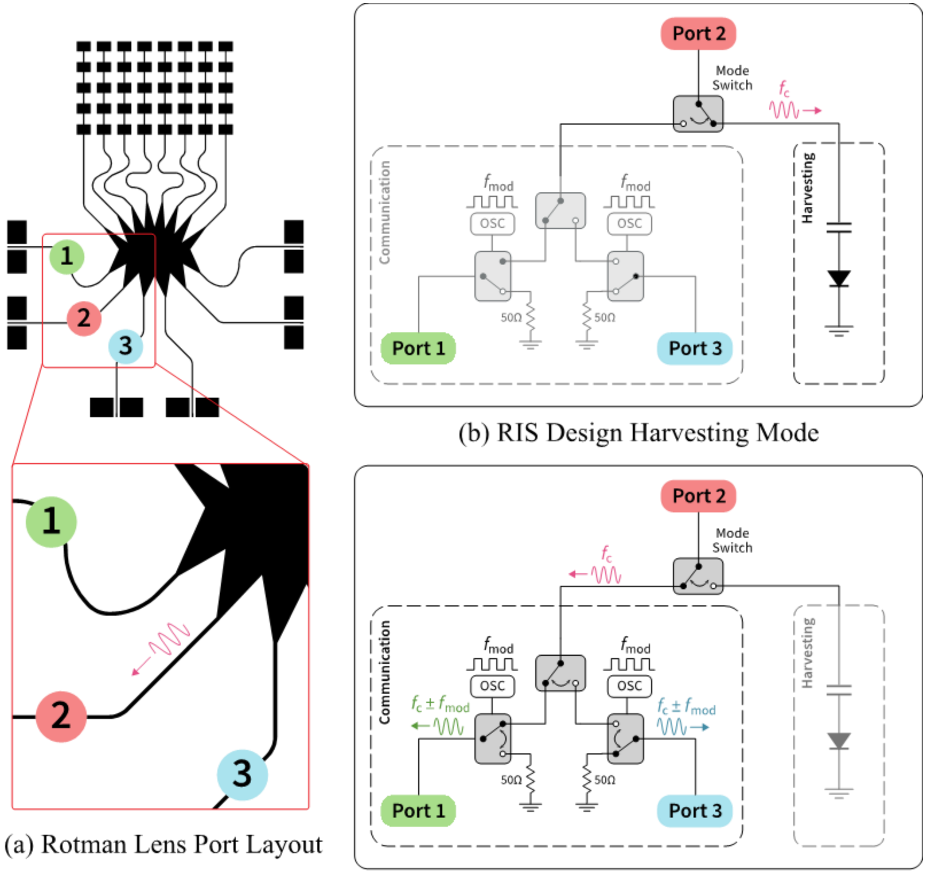
Sensitivity of the Systems



- **6dB lower turn-on power density**
- Higher efficiency at all measured power densities
- **21-fold increase** in harvested power

Autonomous Printed Planar Rotman Lens-Based Reconfigurable Intelligent Surface (RIS) to Bypass Blockage & Enhance Network Densification

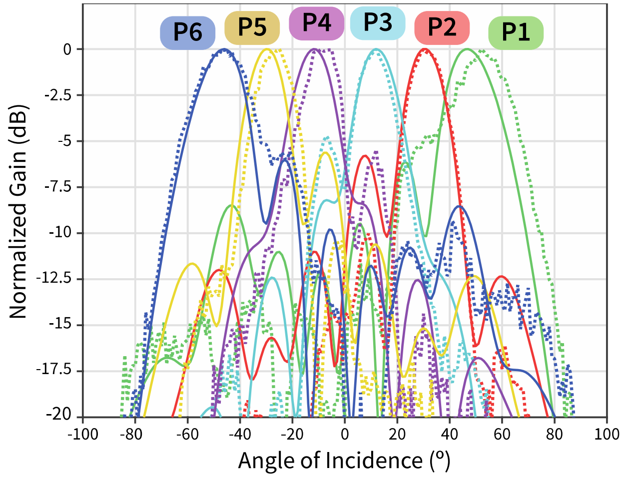




(a) Rotman Lens Port Layout

(b) RIS Design Harvesting Mode

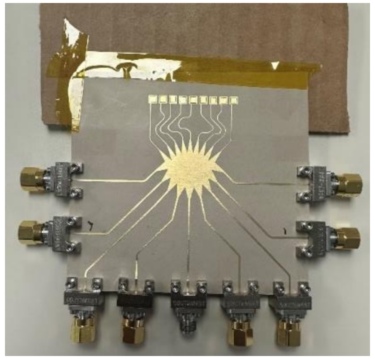
(c) RIS Design Communication Mode



A Converged Optical and mm-Wave, Dual-band, Multi-beam Rotman Lens Metasurface for 5G+/mmW Base Stations and Network Densification

- **Motivation:**
- Current base station design is too complex for dense 5G networks:
  - Individual systems required for operation at different frequencies
  - Complex beamforming devices for single beam at-a-time
- **Goal:** Simplification of the 5G/mmWave base station for network densification using opto/RF metasurfaces:
  - Modulation in the optical domain
  - Optical to mmWave conversion at photodiode
  - Transmission through a singular device: Dual-band, Multi-beam Rotman Lens

SNR of at least 30dB and BER<10^{-6} at 28/39GHz for multi-beam at-a-time transmission



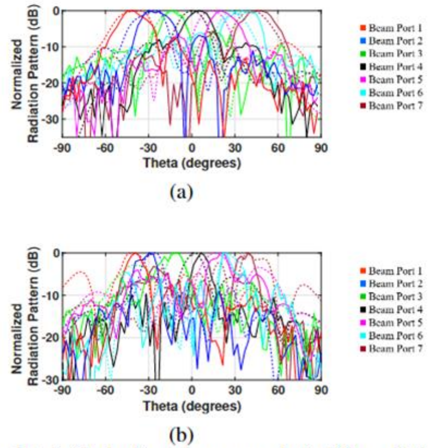


Fig. 4. Simulated (dashed) and measured (solid) radiation patterns of integrate

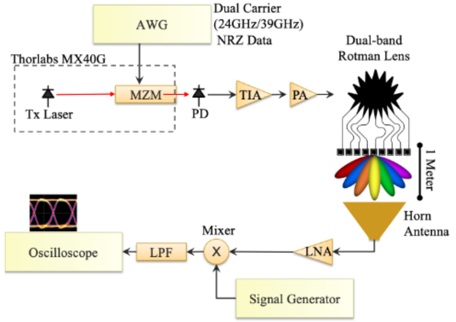


Fig. 5. Schematic of the experimental proof-of-concept dual-band, optical-to-mmW converged Rotman lens system for 5G/mmW base station simplification.

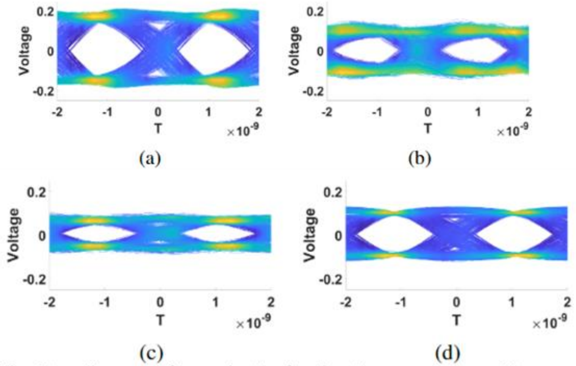
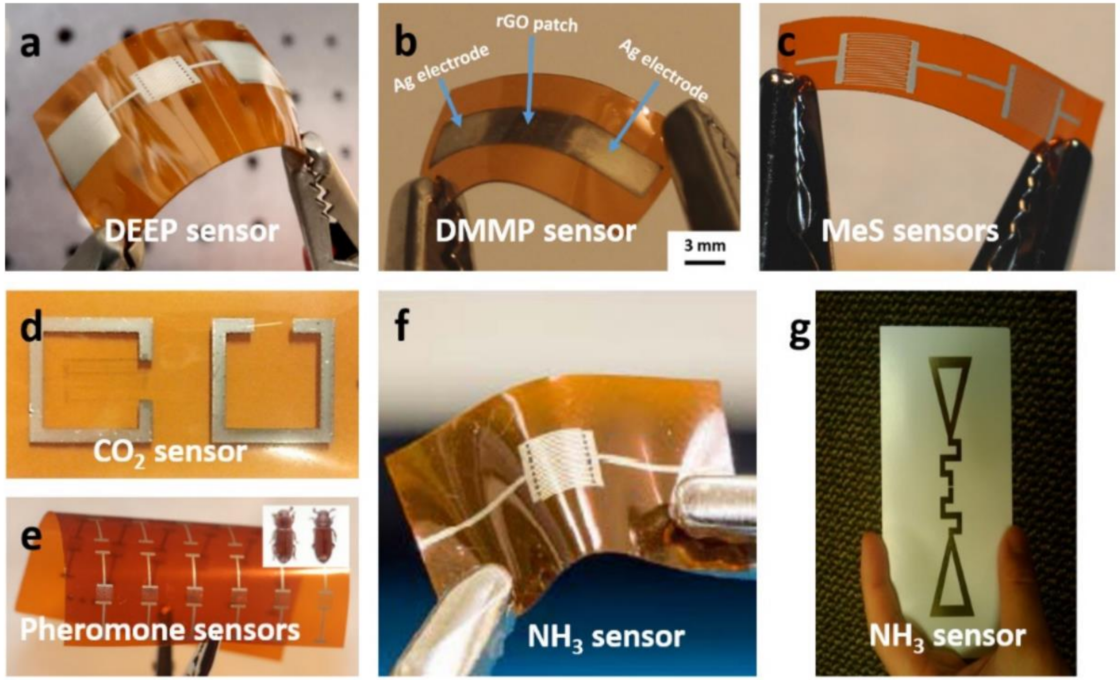
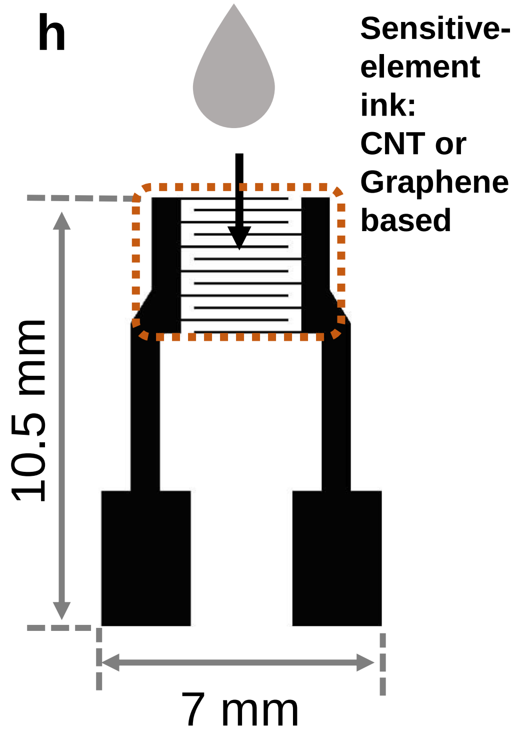


Fig. 10. Eye diagrams for optically feeding beam port 4 and beam port 6 of the dual-band Rotman lens to demonstrate multi-beam at a time interrogating at first beam peak (0°) at (b) 24 GHz and (b) 39 GHz and interrogating at the second beam peak (30°) at the (c) 24 GHz and (d) 39 GHz.

L.Smith, C.Lynch, C.Kaylor, A.Campos, L.Cheng, S.Ralph and M.M.Tentzeris, “A Converged Optical and mm-Wave Dual-Band Multi-Beam Rotman Lens Antenna System Enabling Simplified Designs of 5G/mmW Base Stations and Network Densification”, presented in IEEE IMS 2023

Additively Manufactured Zero-Power RIS-Integrable Sensors





(a) Chemical warfare nerve agent simulant diethyl ethylphosphonate (DEEP)
(b) Chemical warfare nerve agent simulant dimethyl methylphosphonate (DMMP).
(c) Chemical warfare blister agent simulant methyl salicylate.
(d) Resonator sensor for CO2.
(e) Sensors for the aggregation pheromone of flour beetles.
(f) - (g) Sensors for NH3.

(h) Interdigitated electrode design to increase surface area

- Sensitive element is deposited between fingers
- Composition on target analyte
- CNT functionalized with different molecules

Is it possible to achieve interrogation ranges of 1km+ for <20uW tag consumption?

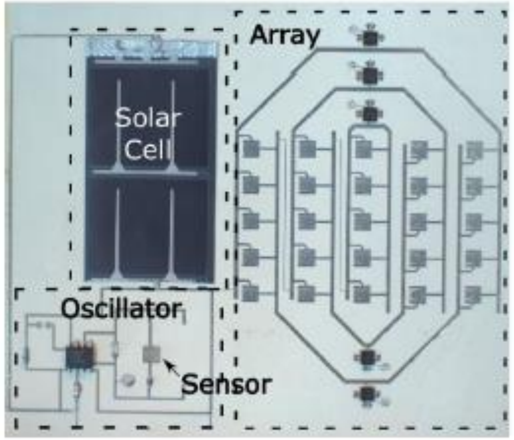
Van-Atta reflect-array: Advantages

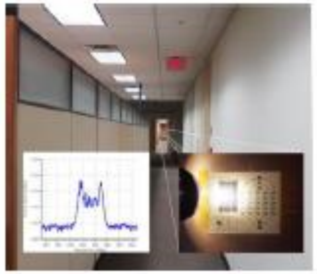
- Unique combination of properties
  - Arbitrarily high RCS (fully scalable)
  - Largely angle independent monostatic response
  - Cross-polarized response
- Reader system consequences
  - High frequency operable (unused bands)
  - High gain, compact, reader antennas (long range)
  - Narrow beamwidth reader antennas (clutter isolation)

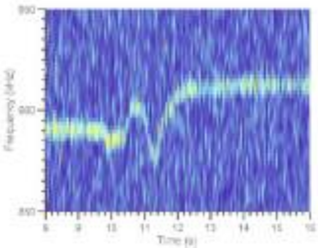
- Operational advantages
  - <u>**Unprecedented (angle independent) reading range (1km+)**</u>
  - Extremely high clutter-induced-interference isolation
  - Compactness

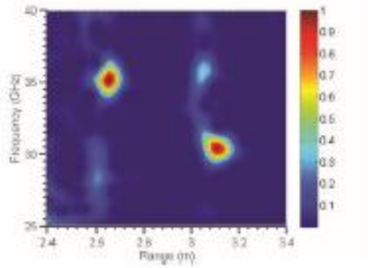
Printed, flexible, backscatter-modulation Van-Atta sensor km-Range "patch" structure

- Active backscatter-modulation Van-Atta
- All the advantages of the passive Van-Atta + non-linear response
- Enables this new structure with
  - Ultra-long-range reading capabilities (up to several kilometers)
  - Outdoor or indoor energy autonomy with solar cell:
    - Ultra-low power consumption (20uW)
  - Almost immediate integration of any of our printed gas sensors
    - Several on the same platform, in the future
    - Great resolution (below 0.5m)







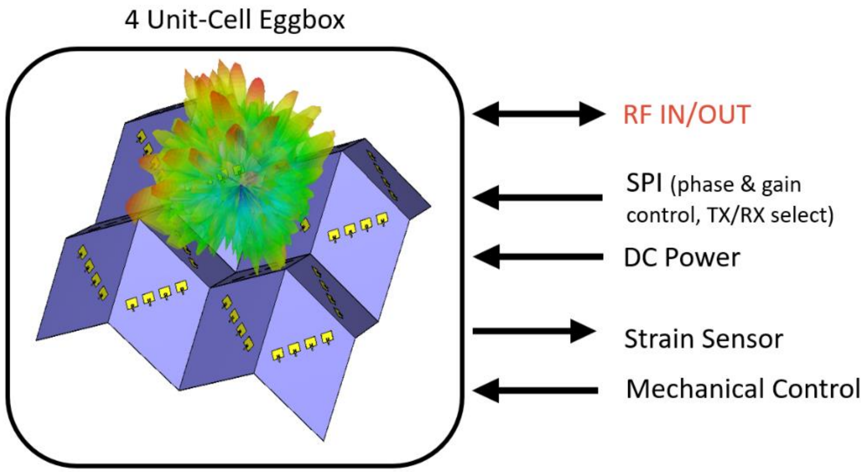


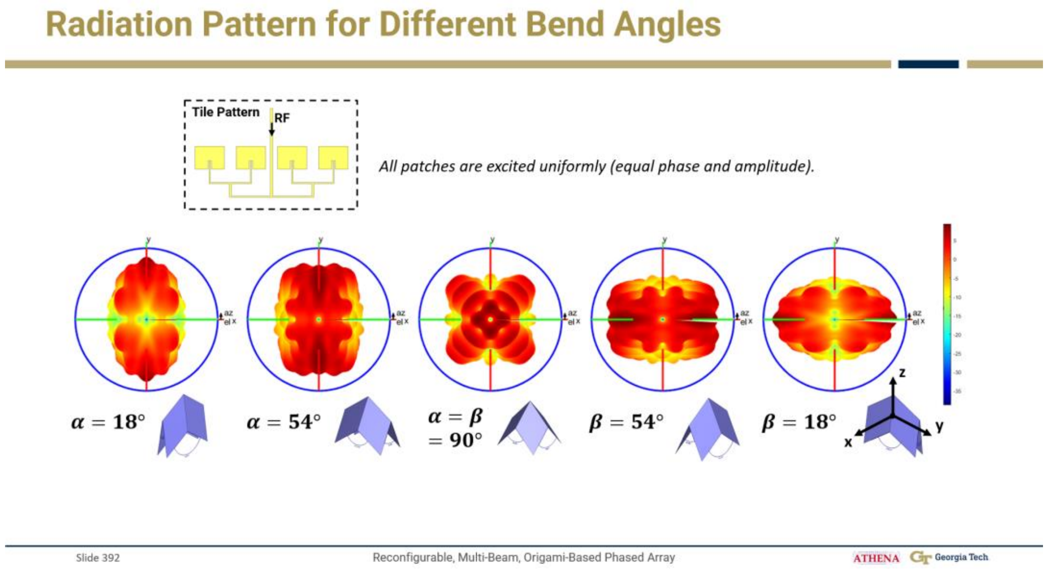
J.Hester and Manos M. Tentzeris, "A mm-Wave Ultra-Long-Range Energy-Autonomous Printed RFID-Enabled Van-Atta Wireless Sensor: at the Crossroads of 5G and IoT", *IEEE International Microwave Symposium (IMS)*, 2017, accepted

J.Hester and M.M.Tentzeris, ``Inkjet-Printed Flexible mm-Wave Van-Atta Reflectarrays: A Solution for Ultralong-Range Dense Multitag and Multisensing Chipless RFID Implementations for IoT Smart Skins", EEE Transactions on Microwave Theory and Techniques, Vol.64, No.12, pp.4763-4773, December 2016.

“Morphing” Phased Array with Virtually “Limitless On-Demand” (Non-Discrete) Reconfigurability States

- Limitless On-Demand Reconfigurability States
- Wide range of coverage and on-the-fly interference mitigation.
    - Scan angles reaching near 180°.
    - Enabled by the eggbox-shaped origami structure which can dynamically manipulate its shape based on practically “**limitless**” **origami tessellations**, in addition to *electronic beam-steering*.
- Modular tile-based approach allows for the **selective activation** of individual tiles and their function as TX or RX.

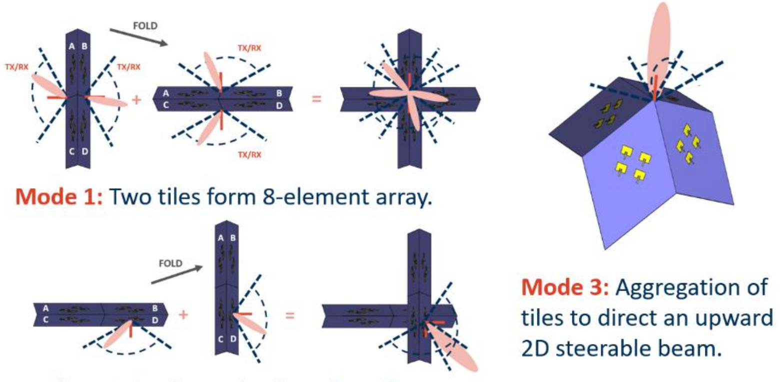




Each element is individually controlled in amplitude & phase granting independent control of 4 beam patterns enabling 360-degree coverage.

"Morphing" Phased Array with Virtually "Limitless On-Demand" (Non-Discrete) Reconfigurable States

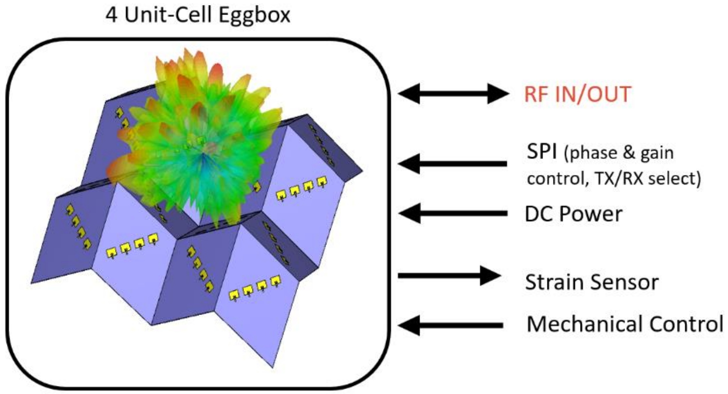
- Limitless on-demand reconfigurable states.
- Wide range of coverage and on- the-fly interference mitigation.
    - Scan angles reaching near 180°.
    - Enabled by the eggbox-shaped origami structure based on particularly limitless origami tessellations, in addition to *electronic beam steering*.
- Modular tile-based approach allows for the **selective activation** of individual tiles and their function as TX or RX.

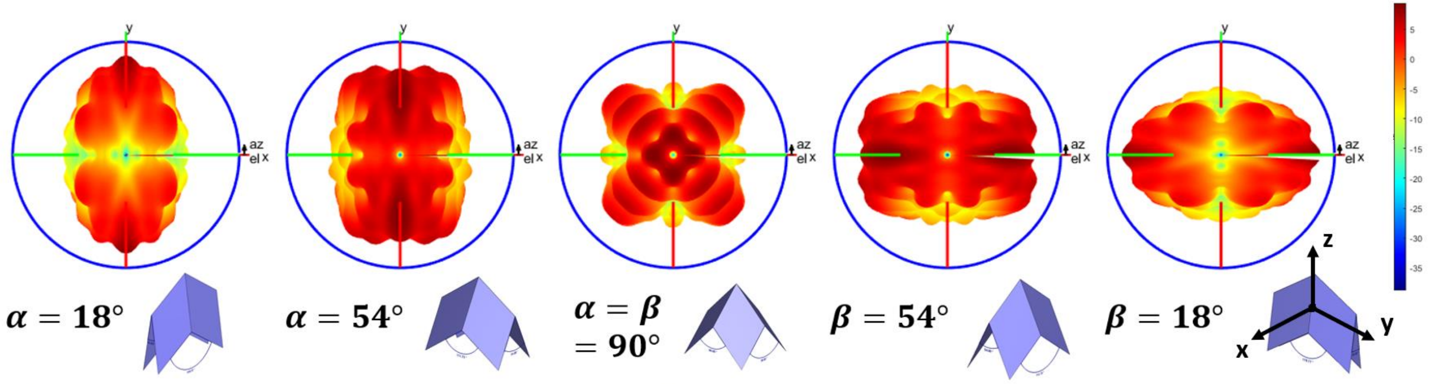


Mode 1: Two tiles form 8-element array.

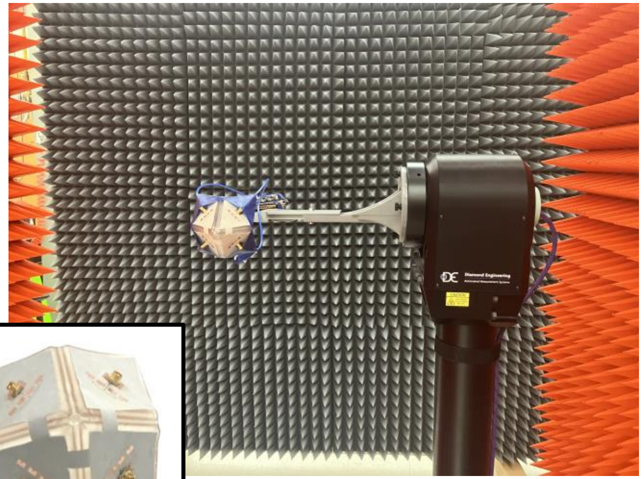
Mode 2: Selective activation of 1+ tiles.

Mode 3: Aggregation of tiles to direct an upward 2D steerable beam.



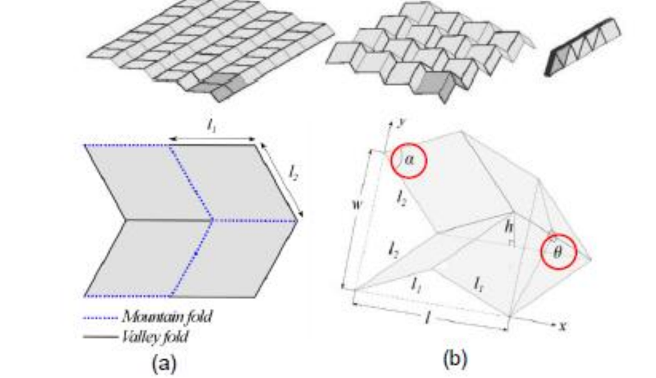


Radiation Pattern for Different Bend Angles

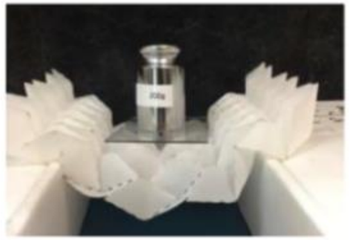


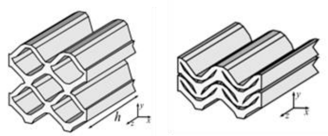
1 Unit Cell

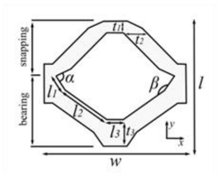
[4D Printed] "Shape Morphing" Deployable Antenna Systems

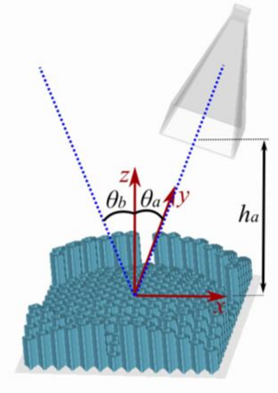


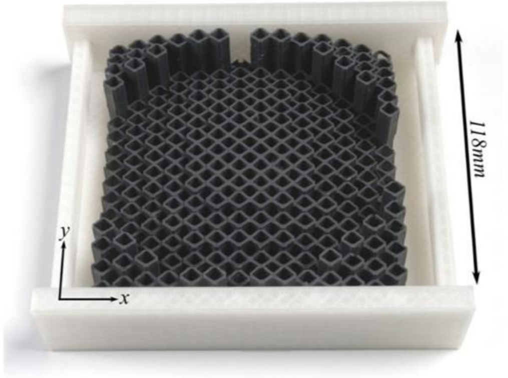
Unit cell of MiuraFSS in (a) flat state (180°) (b) folded state

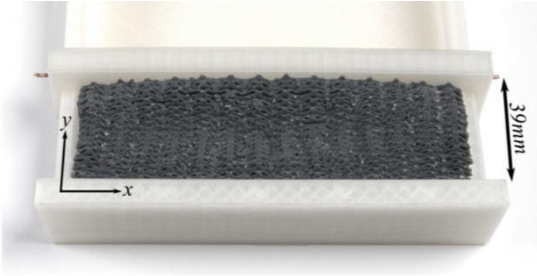


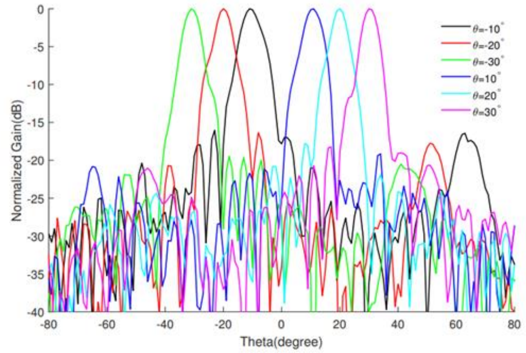


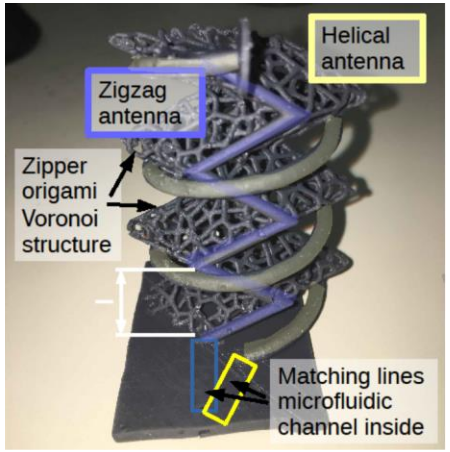


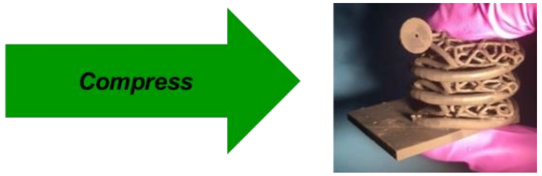


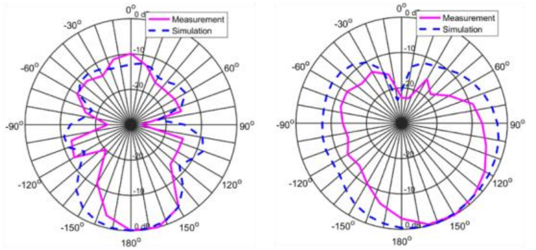








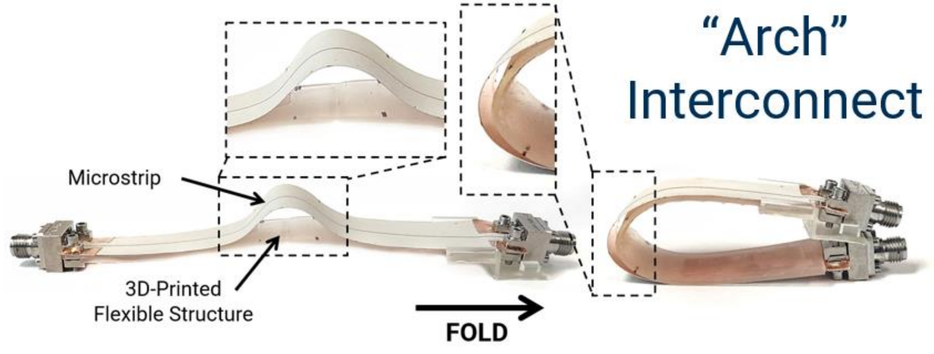


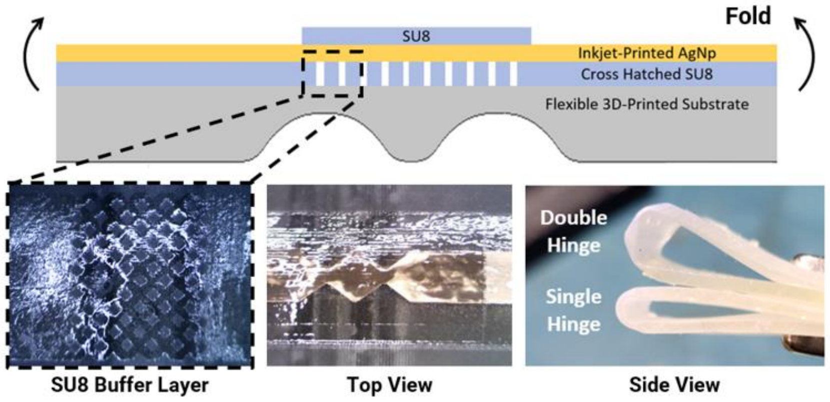


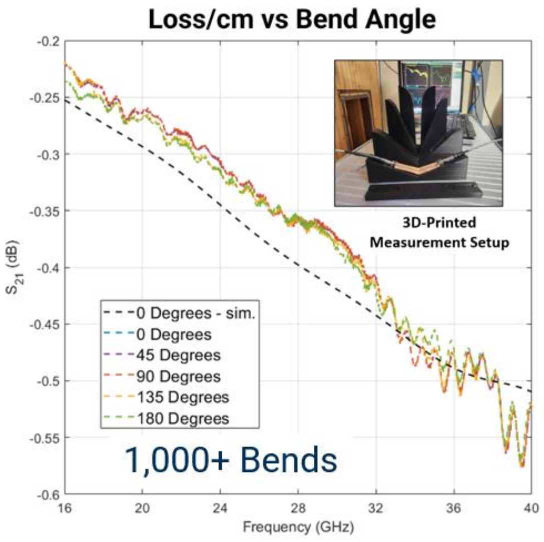
NASA Starshade Inspired for Space WPT and UAV Wireless Charging

Additively Manufactured Foldable Hinge Interconnects

"Arch" Interconnect

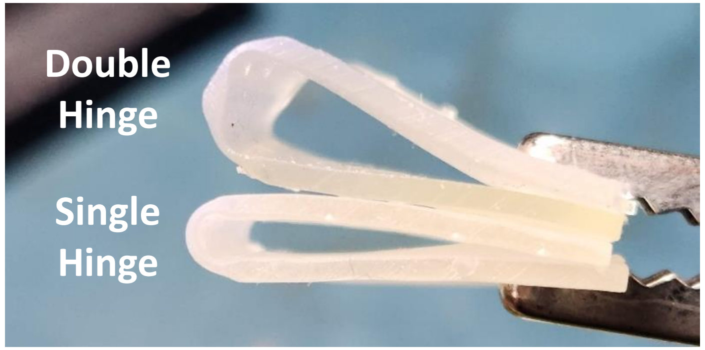


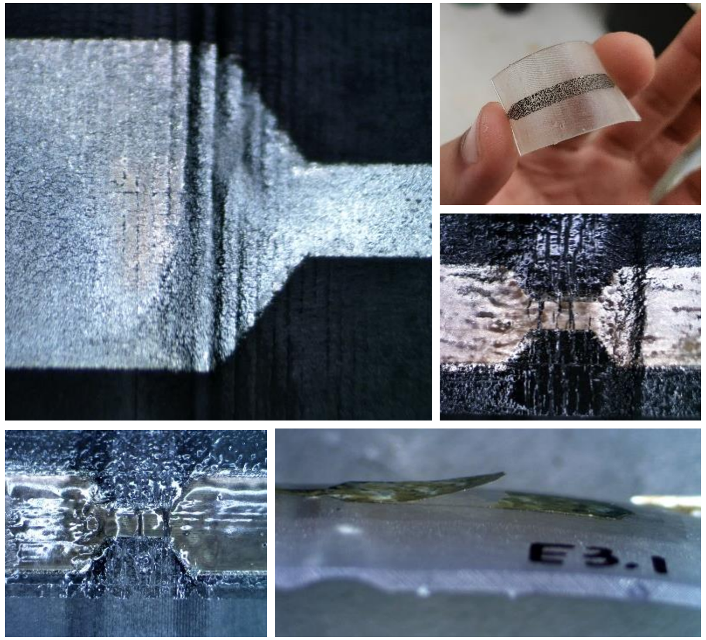




Additively Manufactured
Dielectric Sandwich
"Double Hinge"

- *Repeatable* folding of RF interconnects.
- Multi-material hybrid inkjet/3D-printing process.
- **Flexible material**.

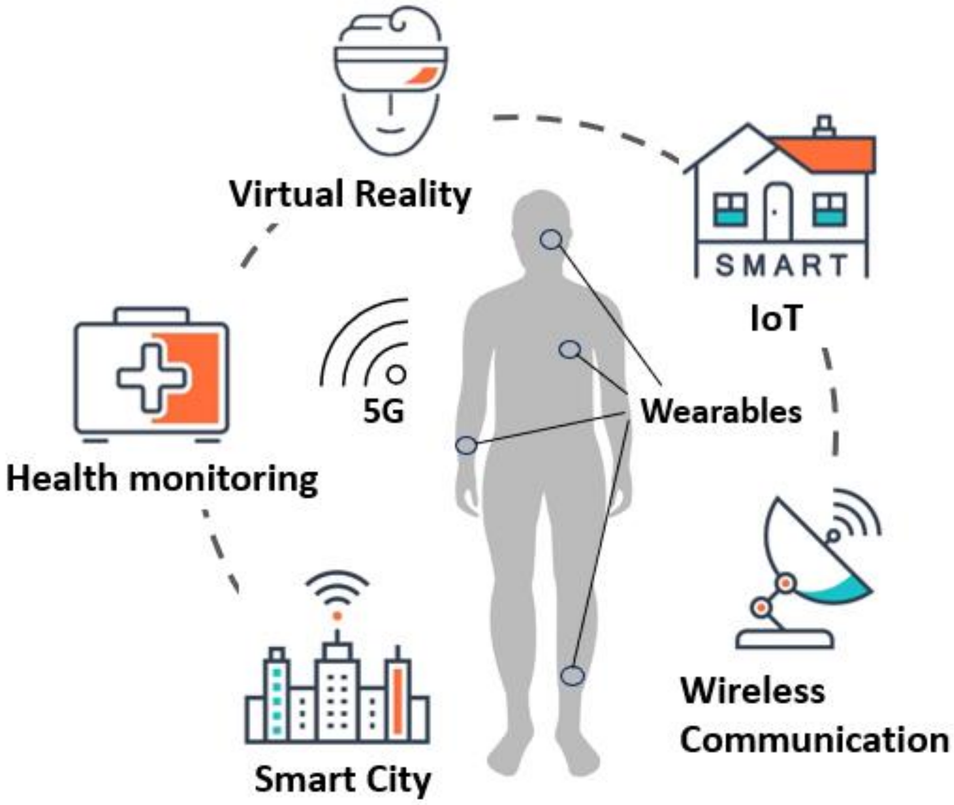




Issues that can occur under repeatable folding: cracking, peeling, surface wetting issues, …

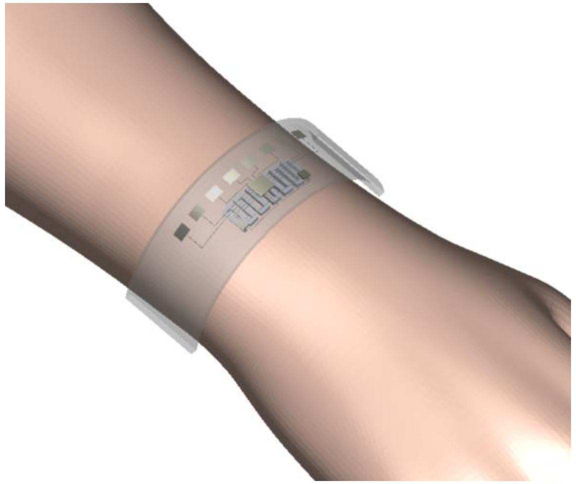
5G-mmW Additively Manufactured Wireless Wearables

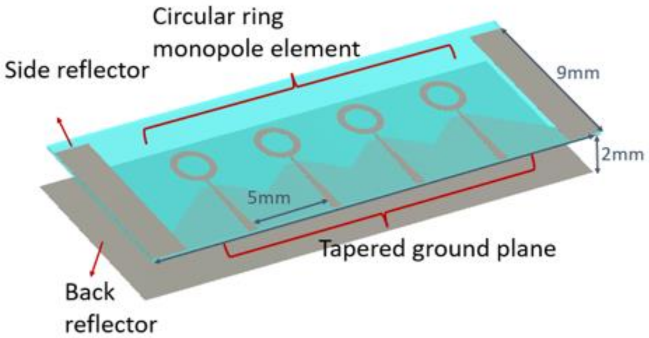
- Increasing demand for future System-on-Package designs
  - real-time response
  - deployable packaging
  - highly-integrated modules
- Flexible phased arrays
  - Support various platforms
  - adaptive beam steerability
  - deployable structures

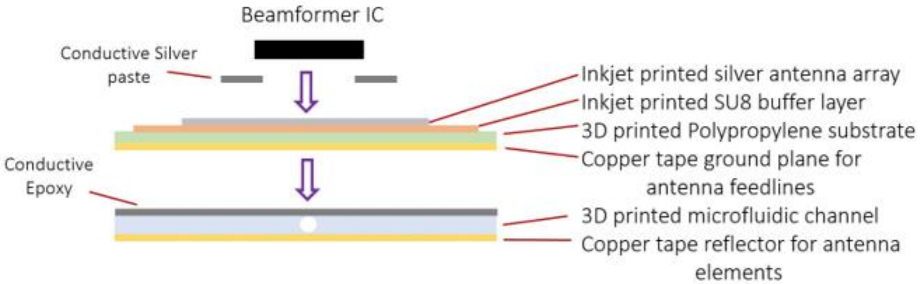


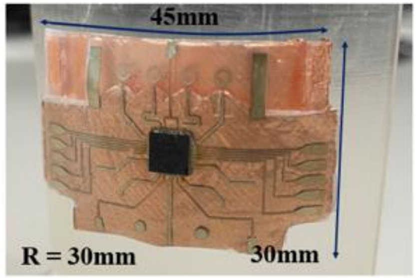
UWB Flexible On-package Arrays for Wearable Applications

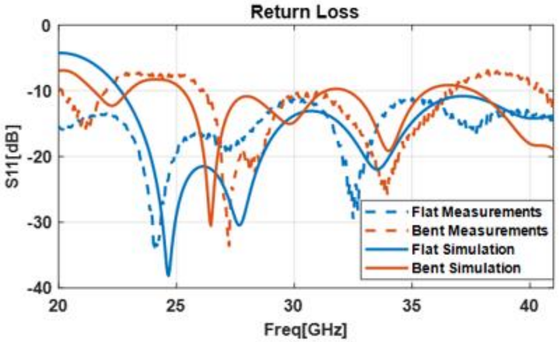
- Additively manufactured flexible on-package phased array with an integrated microfluidic channel.
- The attached beamformer IC is sustainable for practical bending radii in flexible wearable applications.
- Low-temperature IC alignment/assembly process combined with AM can be applied to flexible MCM and SoP designs.

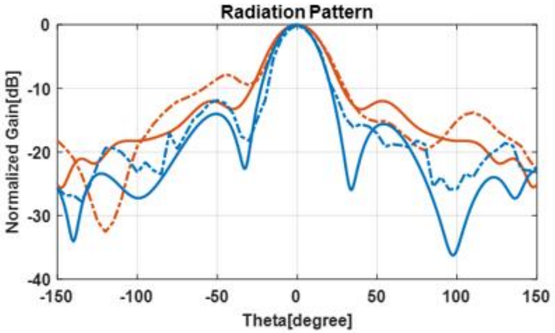






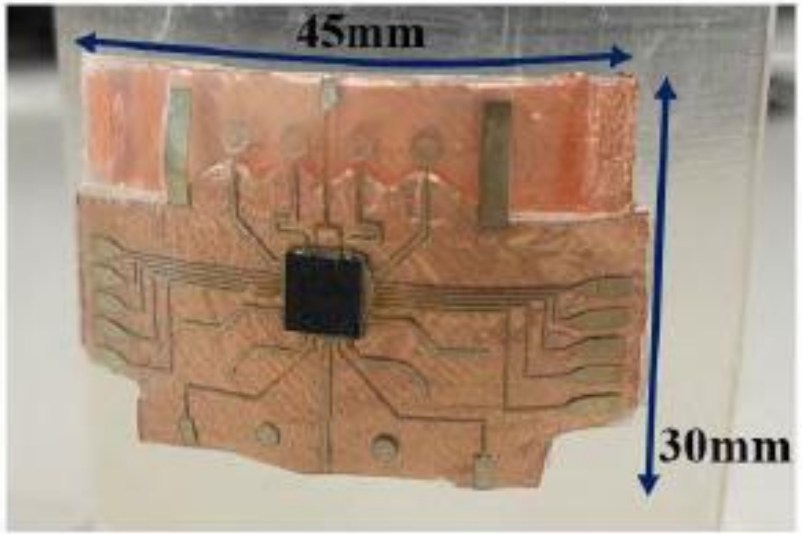


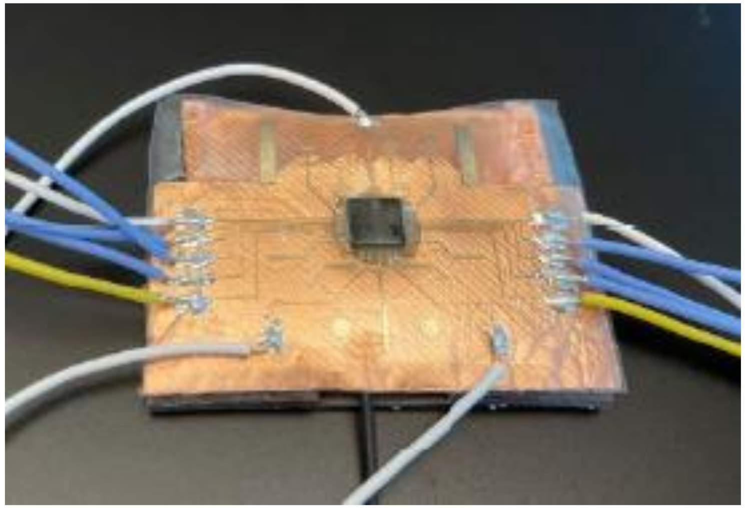


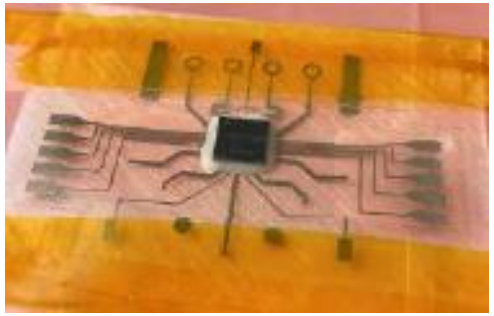


- K. Hu, Y. Zhou, S. K. Sitaraman, and M. M. Tentzeris, “Additively manufactured flexible on-package phased array antennas for 5G/mmWave wearable and conformal digital twin and massive MIMO applications,” Sci Rep, vol. 13, no. 1, p. 12515, Aug. 2023, doi: 10.1038/s41598-023-39476-w.

Flexible SoP Modules on PET and Integrated Microfluidics

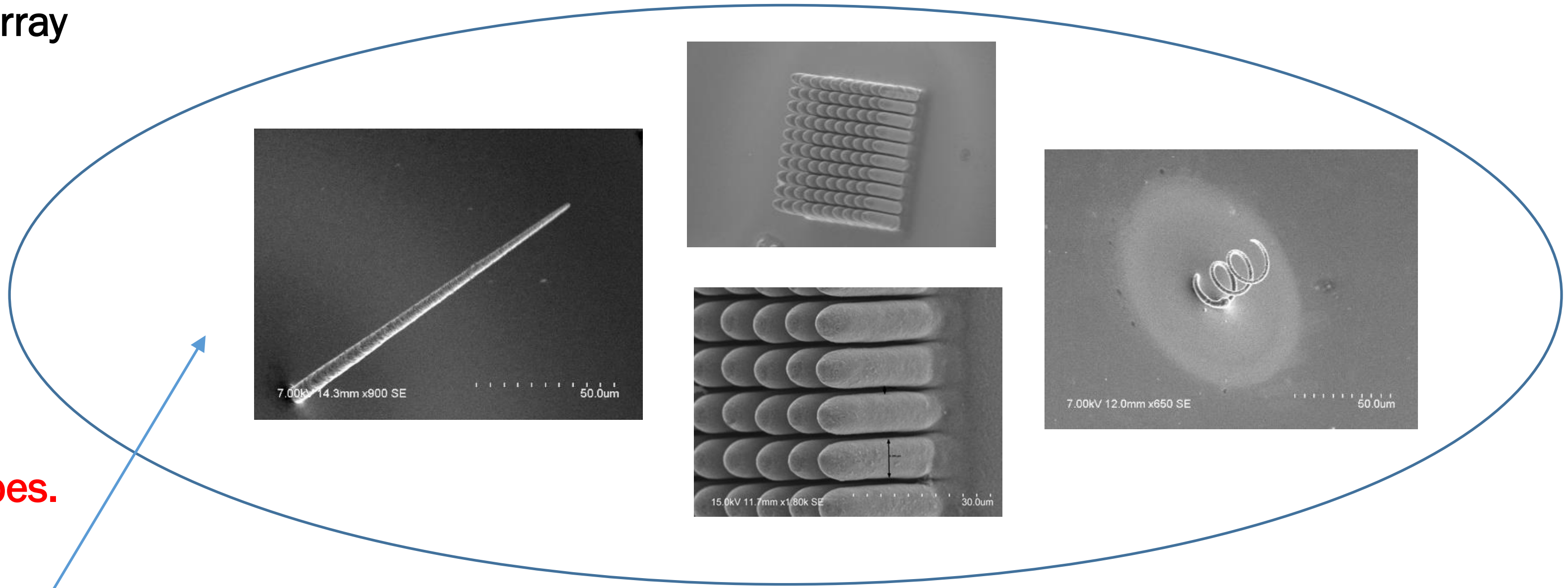


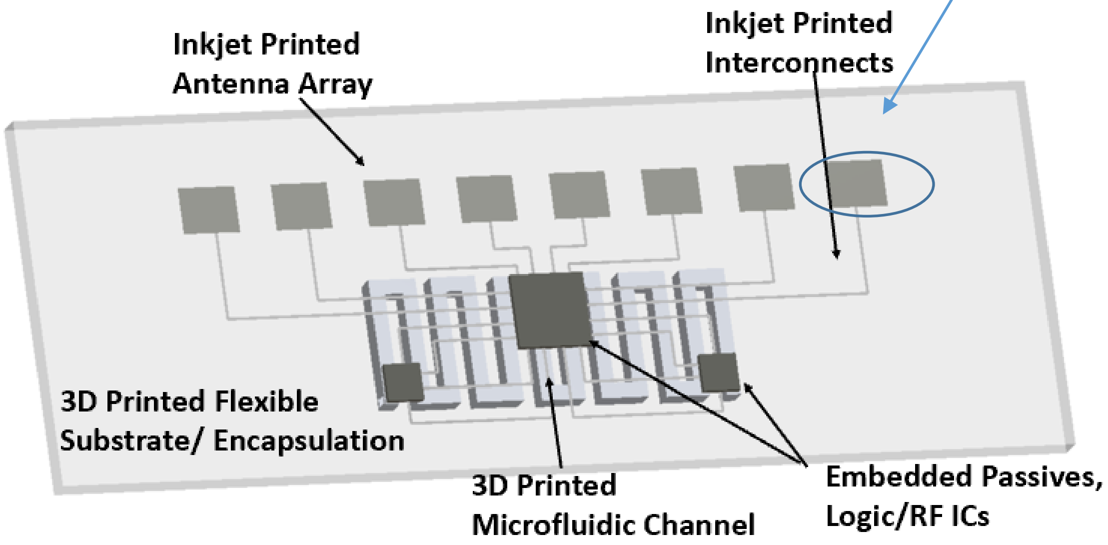


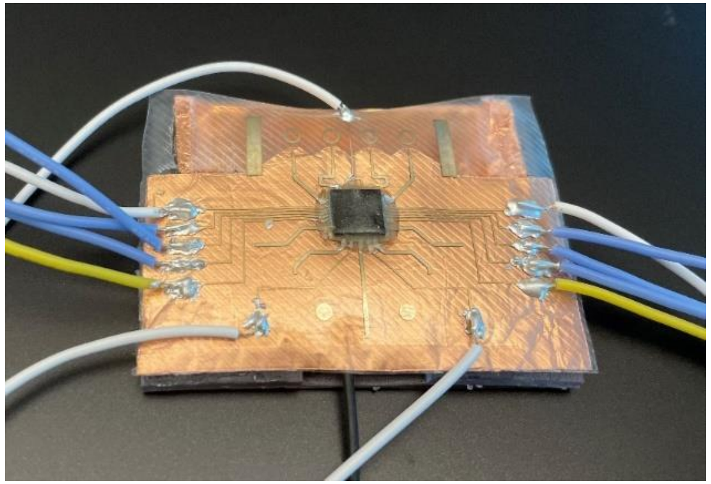


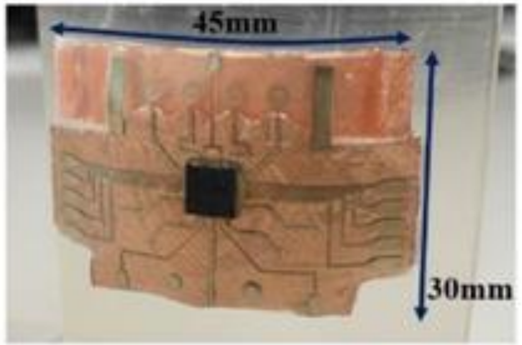
AM Flexible Wearable Phased Array w/ Integrated Microfluidic Capabilities

- 5G Inkjet printed 2.5D ultra-wideband antenna array
- 3D printed Polypropylene substrate and encapsulation
- 3D printed microfluidic channels
- Embedded RFICs with conductive epoxy
- Bendable down to 0.5in radius
- 140deg+ beam steering / flex-calibration
- Plan to extend to sub-THz frequencies using submicron in-house additive manufacturing recipes.

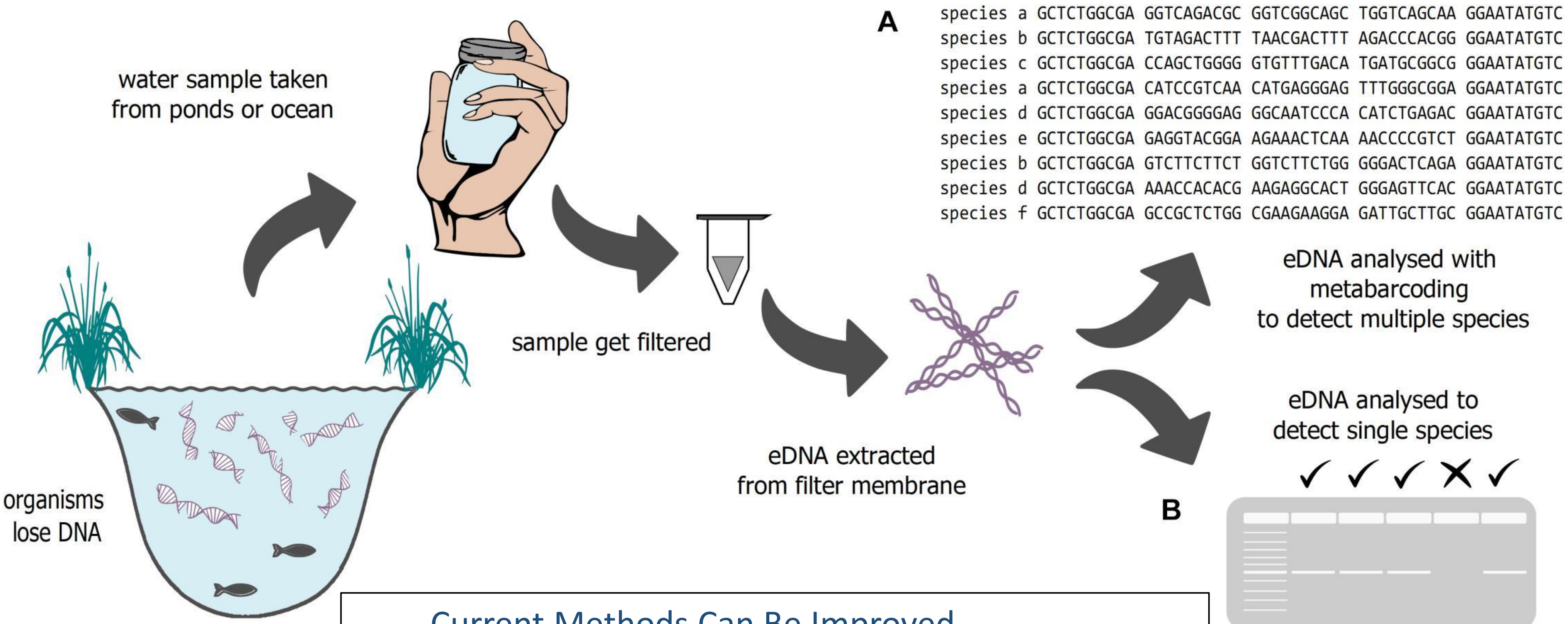








Current eDNA Sensing Methods are Expensive and Time Consuming

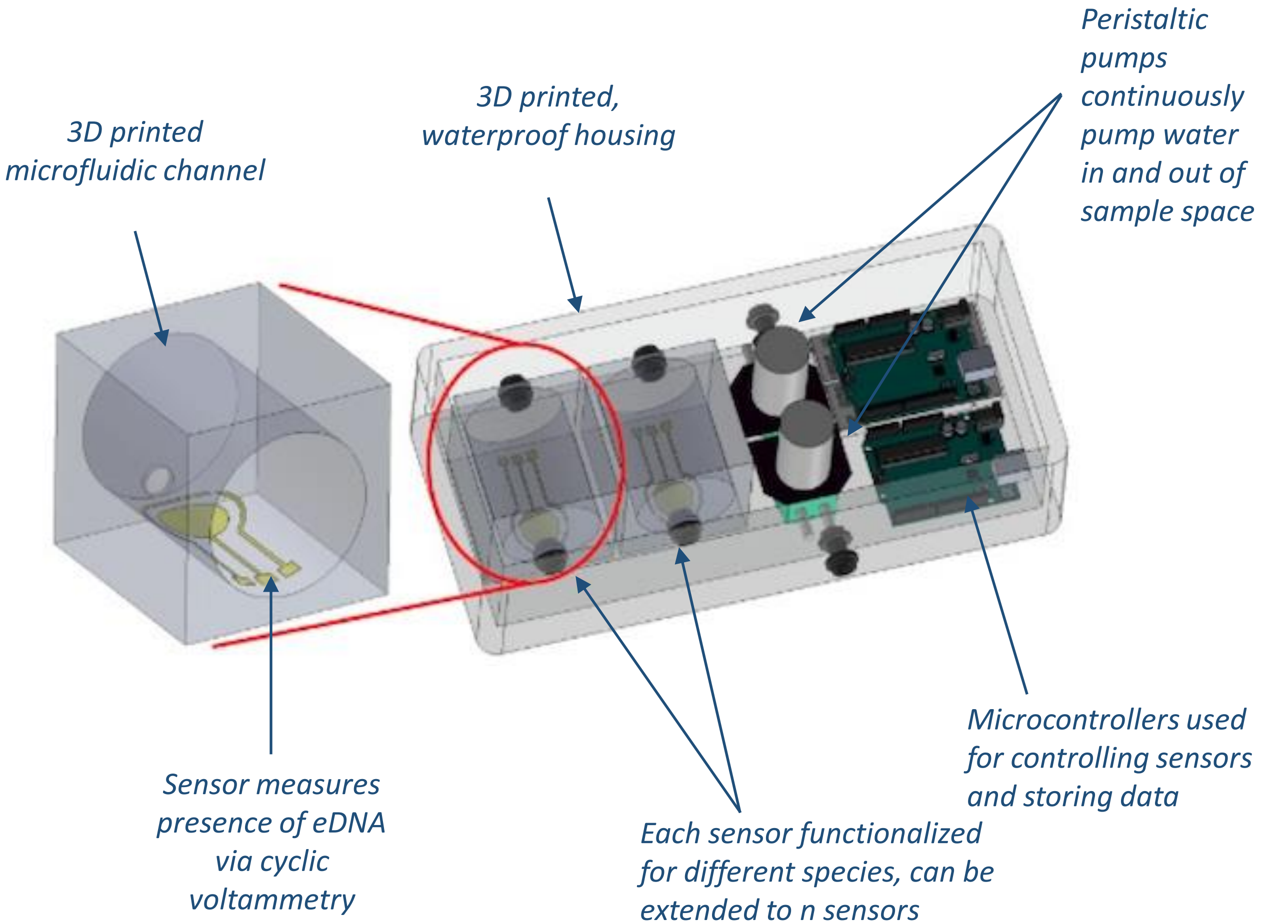


<u>Current Methods Can Be Improved</u>

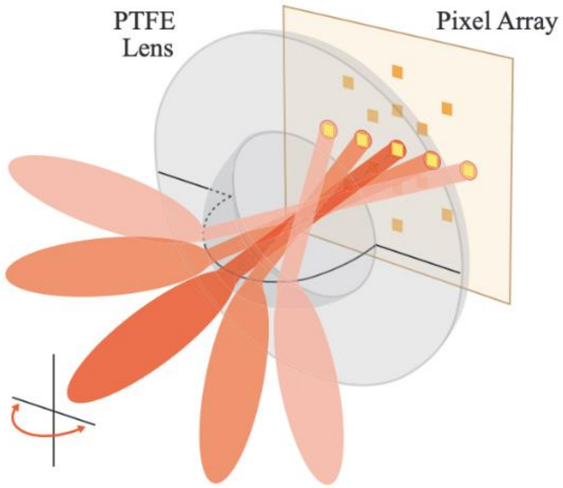
- Takes weeks to ship samples and retrieve data
- Expensive metabarcoding process
- Cannot continuously measure

Low-Cost, High-Throughput, Continuously Measuring, eDNA Sensors Can Be Realized Through Additive Manufacturing Techniques

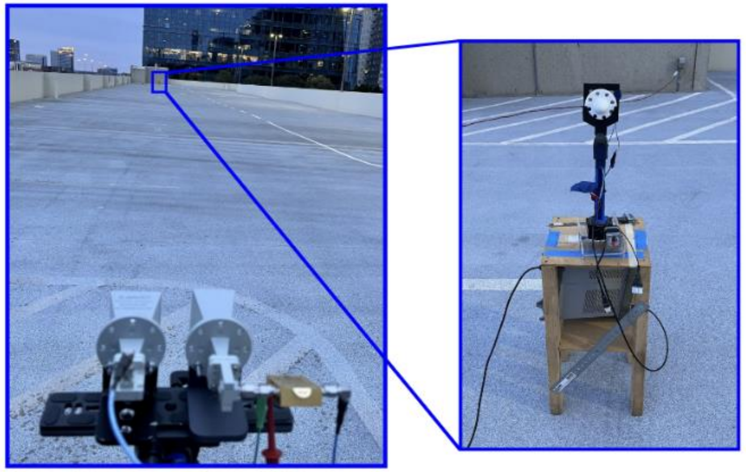
- **3D printed**, **waterproof** architecture holds microcontroller and **low-power** peristaltic pumps and microcontrollers (< 0.1 W per measurement)
  - Assuming 1 measurement/hr
  - Sampled volume of ~ 8000 mm^3
  - Sensitivity of < 200 pL DNA
  - Concentration of eDNA in environment varies wildly from species to species and is often localized in certain areas
- Gold is **corrosion-resistant** to water and will be inkjet printed in the **3D printed microfluidic channels** to realize sensing
- Backscattering-based resistometric interrogation taking advantage of liquid antenna principles



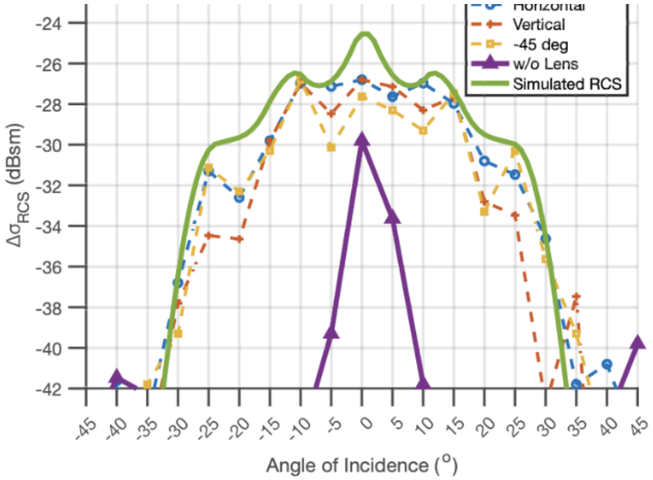
Camera-inspired 3D Lens-based “Zero-Power” Metasurfaces: wide interrogation angle for “agnostic” wireless links



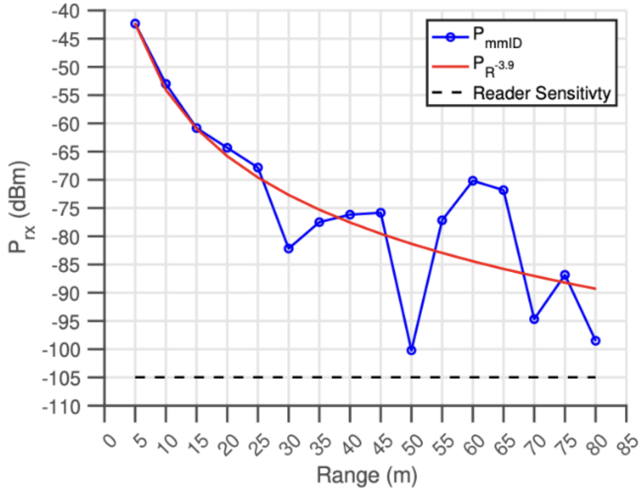
Provides retro-directive behavior through focalizing on the RF ‘pixels’.



Interrogation experimental setup at 80 m.



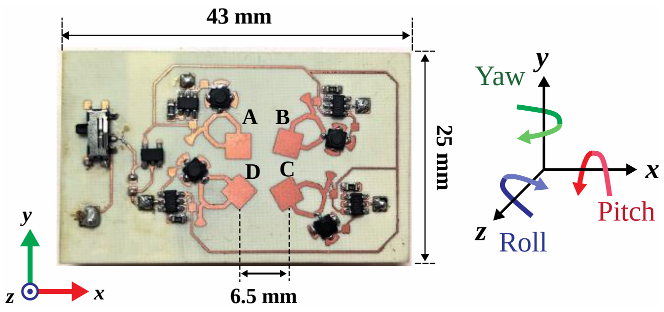
Broad solid angular coverage up to $\pm 28°$ **of -10 dB beamwidth.**



Interrogated up to 80 m away with a proof-of-concept reader.

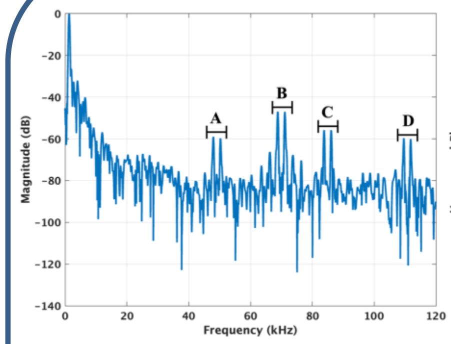
C.A.Lynch, G.Soto-Valle, J.Hester and M.M.Tentzeris, “mmIDs enter the 3rd dimension: A Camera Inspired Broadbeam High-Gain Retrodirective Backscatter Tag”, presented in IEEE IMS 2023

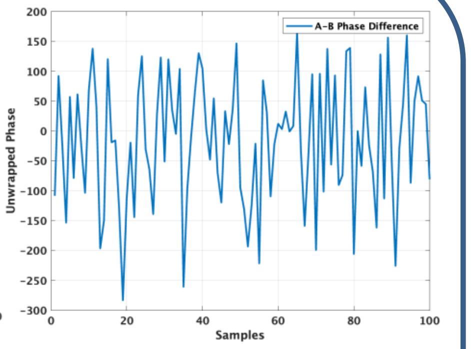
Machine Learning-Enhanced mmID-”Gyro” for 3-Axis Metasurface Orientation Wireless Detection



✓ Low Cost mmWave System

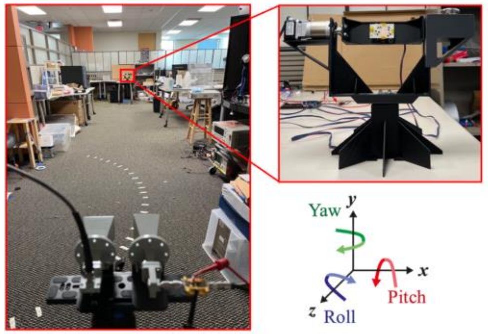
- Ultra-low-power, sticker-like mmWave mmID
- Comprised of four backscattering elements that are multiplexed in amplitude, frequency, and spatial domains
- Each element designed with polarization offset of 15° from each other to allow for angle of rotation encoding
- Cross Polarization antenna configuration utilized to reduce signal interference to reader
- 24 GHz FMCW Radar utilized as reader





✓ Digital Signal Processing

- Amplitude Response of each antenna element
- Phase Difference of neighboring elements using Arctangent Demodulation Algorithm



✓ Data Processing/Machine Learning

- Tag rotated over ± 90°, with increments of 10°, in each axis
- K-Nearest Neighbors (KNN) Algorithm
- Global Dataset of 2.8 million data samples
- 80/20 Train-Test Split

Range	Model A	Model B
0.5 m	99.60%	99.87%
1 m	95.59%	99.85%
2 m	81.19%	99.77%
3 m	67.29%	98.67%
4 m	58.81%	97.95%
5 m	53.29%	93.73%
6 m	47.14%	91.36%
7 m	46.45%	88.51%
8 m	45.89%	85.43%
9 m	45.22%	82.19%
10 m	45.01%	77.88%

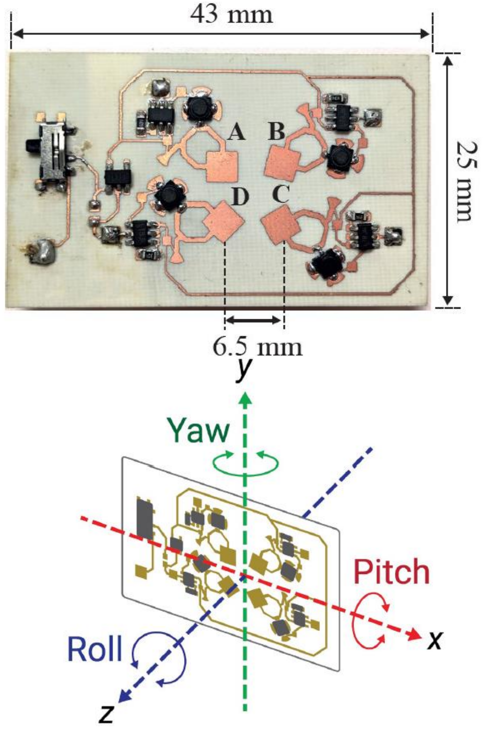
✓ Results

- 2 Models trained
  - Model A: Only Amplitude Response
  - Model B: Amplitude Response and Phase Difference
- Accuracy >91% achieved at up to 6 m with Model B
- Further evaluation to be performed with a finer angular resolution for an even more precise orientation detection

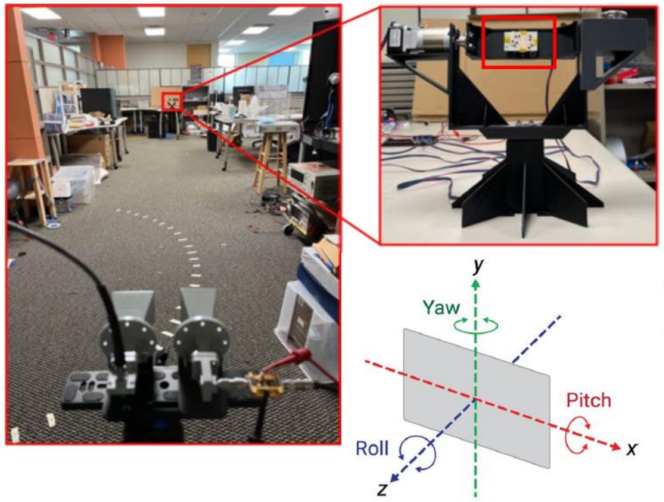
A.Adeyeye, C.Lynch, J.Hester and M.M.Tentzeris, "A Machine Learning Enabled mmWave RFID for Rotational Sensing in Human Gesture Recognition and Motion Capture Applications", Proc. of the **2022 IEEE International Microwave Symposium (IMS),** Denver, CO, June 2022.

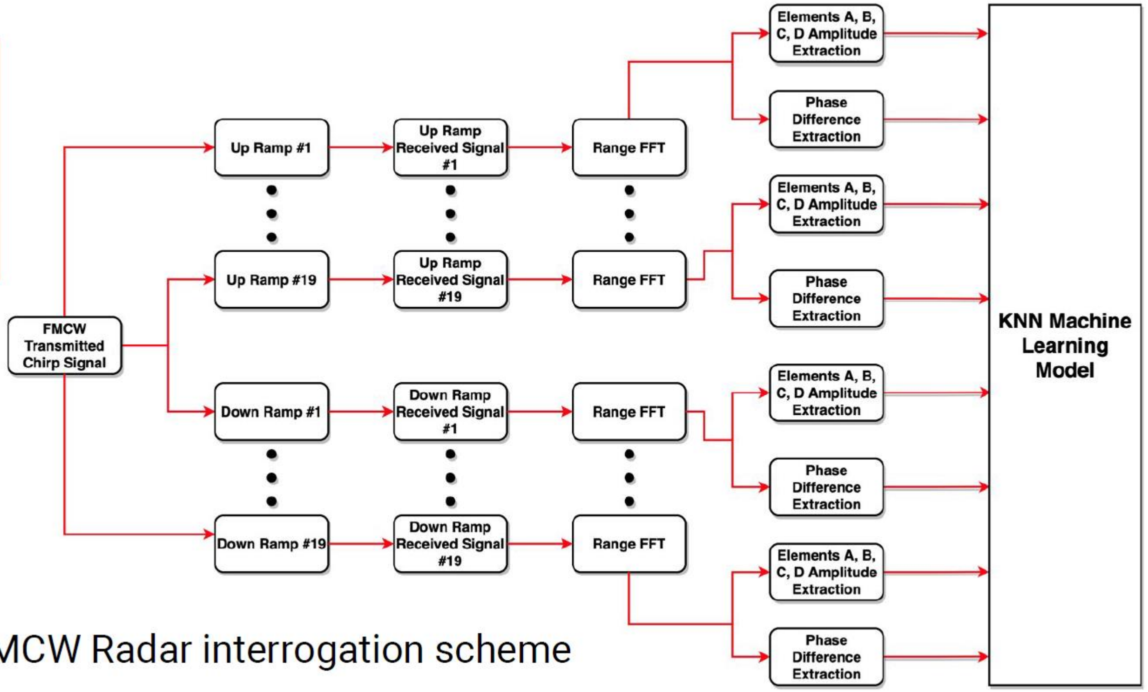
ML-Enhanced mmID for 3-axis Orientation Wireless Detection

- Ultra-low-power, sticker-like mmWave mmID
- Comprised of four backscattering elements multiplexed in amplitude, frequency, and spatial domains
- Tag rotated over ±90°, with increments of 10°, in each axis; K-Nearest Neighbors (KNN) Algorithm
- Accuracy >91% achieved at up to 6 m with model based on Amplitude Response and Phase Difference



Measurement setup and data signal processing chain:



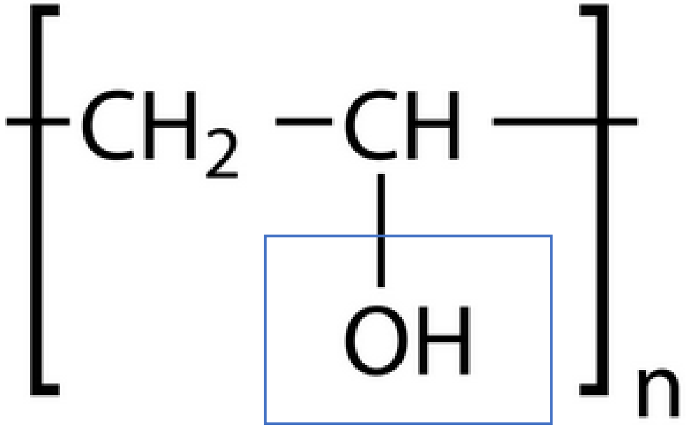


FMCW Radar interrogation scheme

- A.Adeyeye, C.Lynch, J.Hester and M.M.Tentzeris, "A Machine Learning Enabled mmWave RFID for Rotational Sensing in Human Gesture Recognition and Motion Capture Applications", Proc. of the 2022 IEEE International Microwave Symposium (IMS), Denver, CO, June 2022.

Transient Electronics/Polyvinyl-Alcohol (PVA) Material Properties

- Selectively soluble in water, or compounds that can form hydrogen bonds
  - ➢ PVA contains –OH groups on the surface, enabling water solubility
  - ➢ Is also slightly soluble in alcohols such as methanol, ethanol etc…
- Idea: use CSRR to enable tracking of water levels/exposure
- Advantage: **selectively soluble** to water
  - ➢ Alcohol compounds take much more time to be soluble
  - ➢ Sensitivity and selectivity of chemical and physical sensing for RFID tags has been identified as an area which needs improvement [1], using PVA as a sensing element addresses selectivity
- **Biodegradable**
- **Facile fabrication**
  - ➢ Thickness and solubility of the film in water can be controlled easily

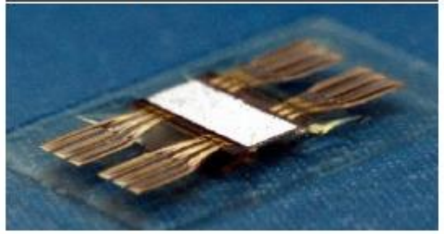


The structure of the PVA polymer. The hydroxyl group boxed in blue allows for hydrogen bonding with water.

[1] Mulloni, Viviana, and Massimo Donelli. "Chipless RFID sensors for the Internet of Things: Challenges and opportunities." Sensors 20.7 (2020): 2135.

Mm-Wave Systems and Packaging with Printing

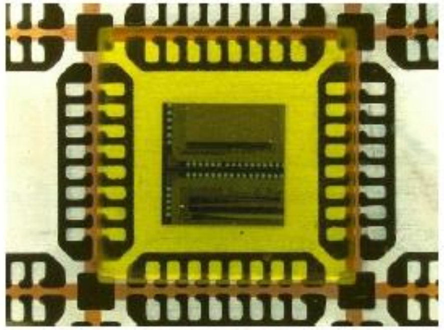
Inkjet Printing



Materials:
Polymer solutions, metallic nanoparticle dispersions, carbon nanomaterial suspensions

- 3D interconnects
- RF substrates
- Die attach

3D Printing

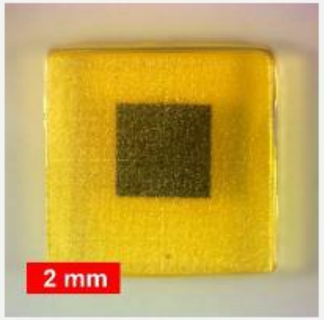


Materials:
Photoactive resins, thermoplastics, ceramic pastes, conductive adhesives

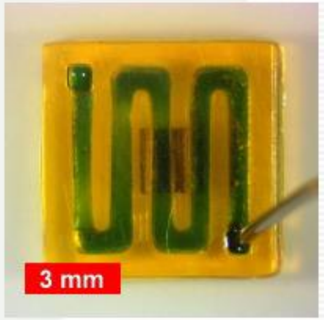
- Dielectric lenses
- Encapsulations
- Die-embedded leadframes

Printed Functional Encapsulants

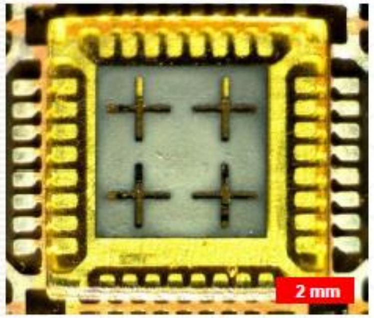
- Stereolithography (SLA) 3D printing directly onto PCBs and dies
- Combine with inkjet printing for metal patterning
- Application-specific encapsulants for RF devices
  - Microfluidic channel-integrated
  - EMI shielding
  - Embedded through-mold vias (TMVs)
- Various materials: rigid acrylate, flexible, ceramic composite



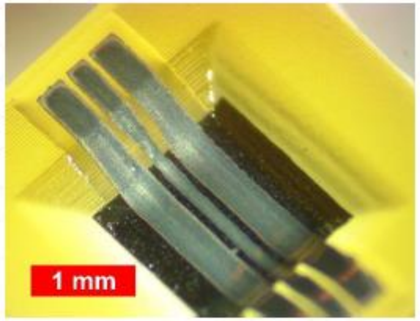
Traditional square



Microfluidic channel-integrated



Periodic FSS shielding

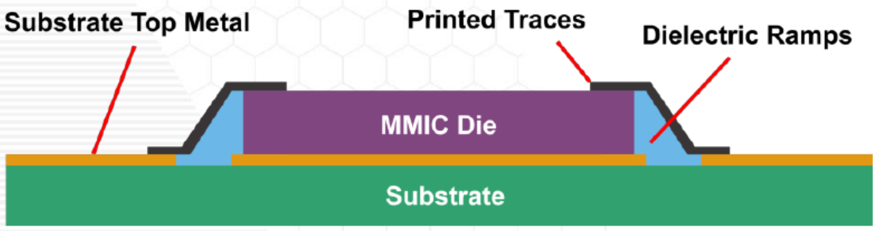


Embedded TMVs

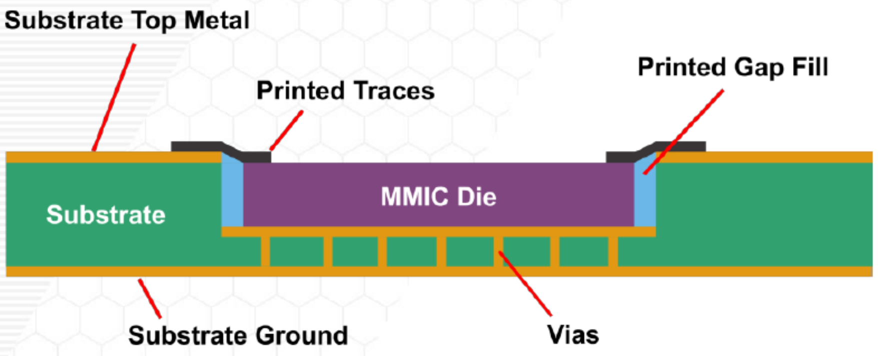
Fully Printable Rugged Conformal Interconnects up to mmW/sub-THz

Printed 3D RF Interconnects

- Goal: mitigate losses from bond wires/ribbons and package transitions for MMIC devices
- Surface mount
  - MMIC die bonded to PCB
  - Dielectric ink printed to form 3D ramps up to surface of die
  - Metallic ink printed to pattern interconnects from PCB to die
- Cavity-embedded
  - MMIC die bonded to GND of cavity within PCB
  - Dielectric ink printed to fill gaps between die and PCB
  - Metallic ink printed to pattern transitions from PCB to die across printed gap fills



Side-view schematic of surface mount scenario



Side-view schematic of cavity-embedded scenario

Fully Inkjet-Printed Ramp Interconnects for Wireless Ka-Band MMIC Devices and Multi-Chip Module Packaging [17]

- First demonstration of fully inkjet printed mm-Wave ramp interconnects for Ka-Band active wireless devices and MCM packaging solutions.
- Printed ramp interconnects with an attenuator die yielding an interconnect insertion loss of approximately 0.45dB/mm at 24.5 GHz.
- With a Ka-band LNA MMIC, ramp interconnects for the RF and DC are inkjet-printed, yielding a maximum aggregate gain of 24.2dB and interconnect insertion loss of approximately 0.57dB/mm.

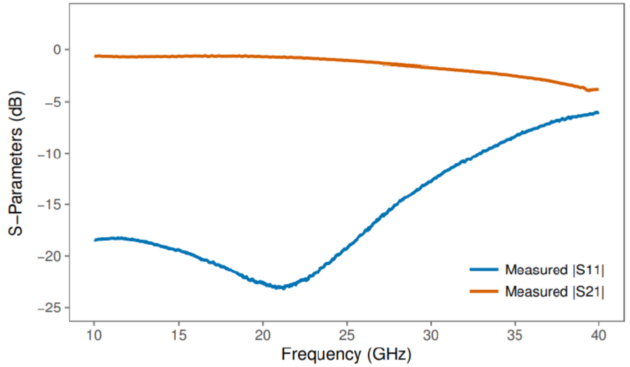


Fig. 3. Measured S-parameters for back-to-back inkjet-printed ramp interconnects with a 0 dB GaAs attenuator die on a MEG 6 laminate.

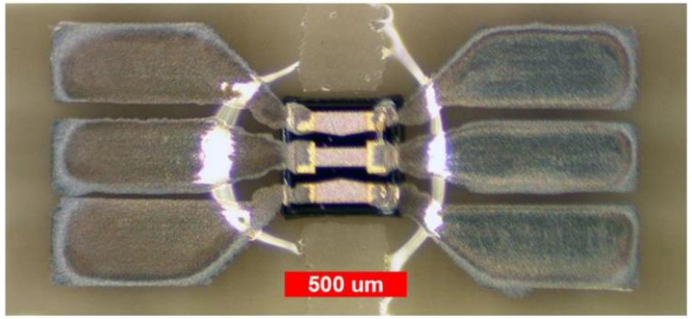
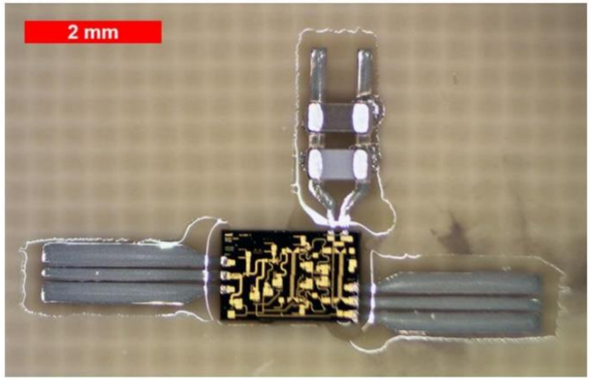


Fig. 2. Inkjet-printed ramp interconnects interfacing a Ka-band GaAs attenuator die.



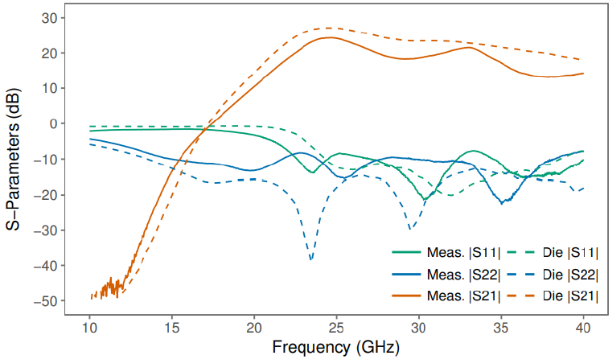


Fig. 5. Measured S-parameters for inkjet-printed ramp interconnects with a Ka-band LNA MMIC on a MEG 6 laminate compared with bare die probing.

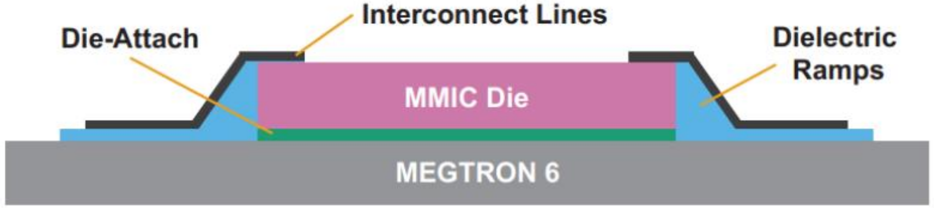
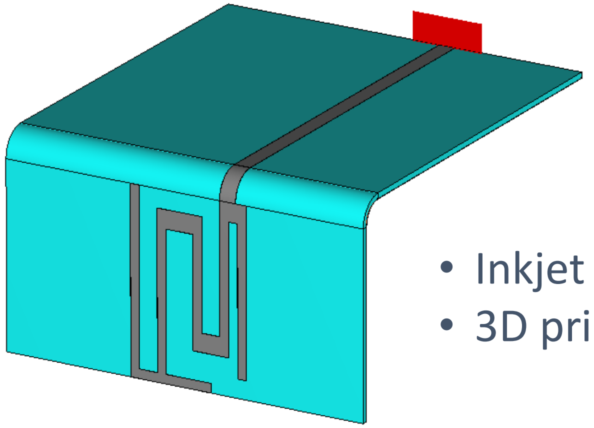


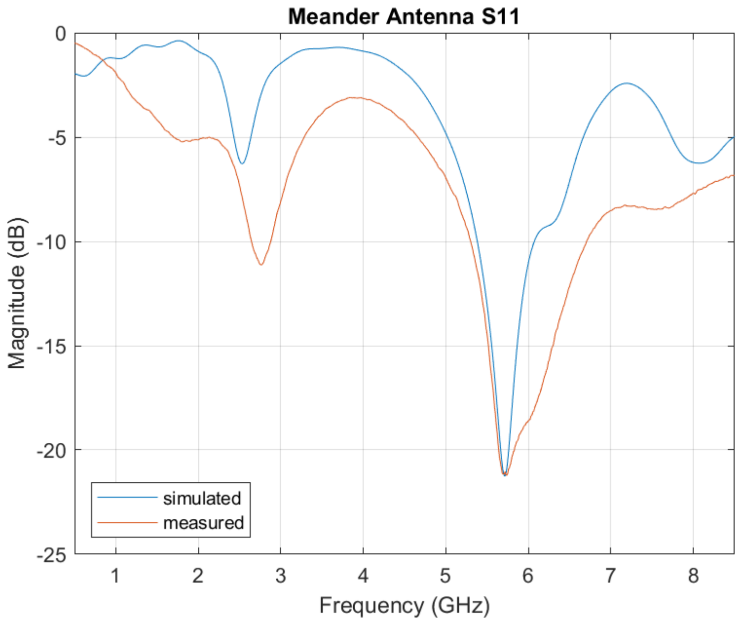
Fig. 1. 2D cross-section schematic of inkjet-printed ramp interconnects for a MMIC die on a MEG 6 substrate

From Radial Interconnects to Foldable Interconnects

silver nanoparticle ink (SNP)
SU8
PP (single layer, flexible)
copper tape
adhesive
PP support

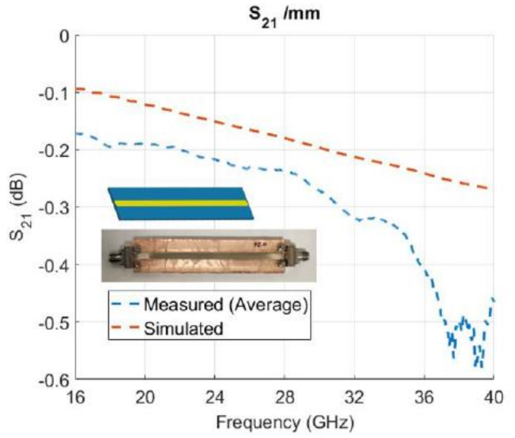


- Inkjet printing on curved bends.
- 3D printed polypropylene substrate

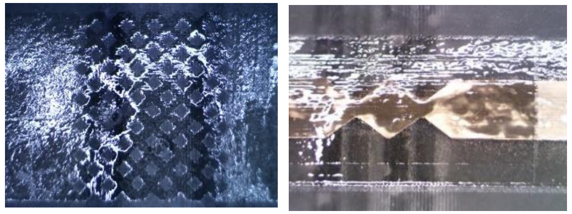


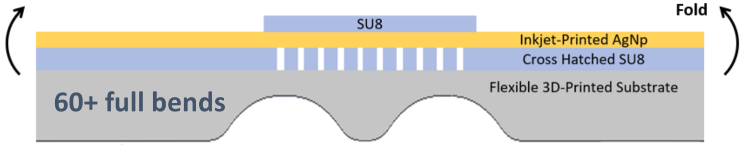
Fully Foldable mm-Wave Hinge Interconnects

- Designed, fabricated and characterized various **interconnect structures** for electrical and mechanical **folding reliability**.
- Utilized:
  1. Creative geometries.
  2. Multi-material, multi-layer stackups.
  3. Inkjet printed materials and 3D printed flexible substrates.
  4. ROGER substrates.

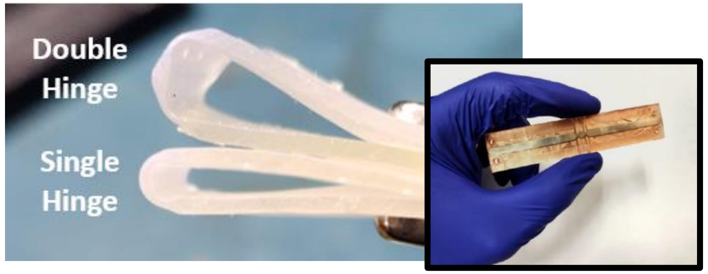


Cross-hatched Buffer Layer

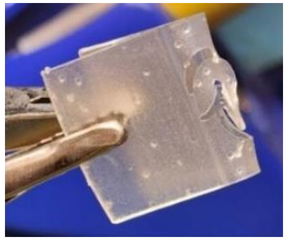




Double-Hinge Dielectric Sandwich Structure

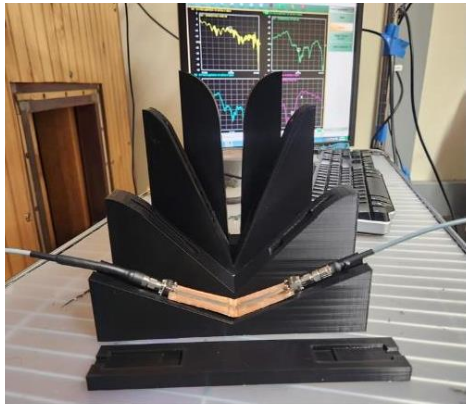


Tilted interconnect with stress-release cutouts



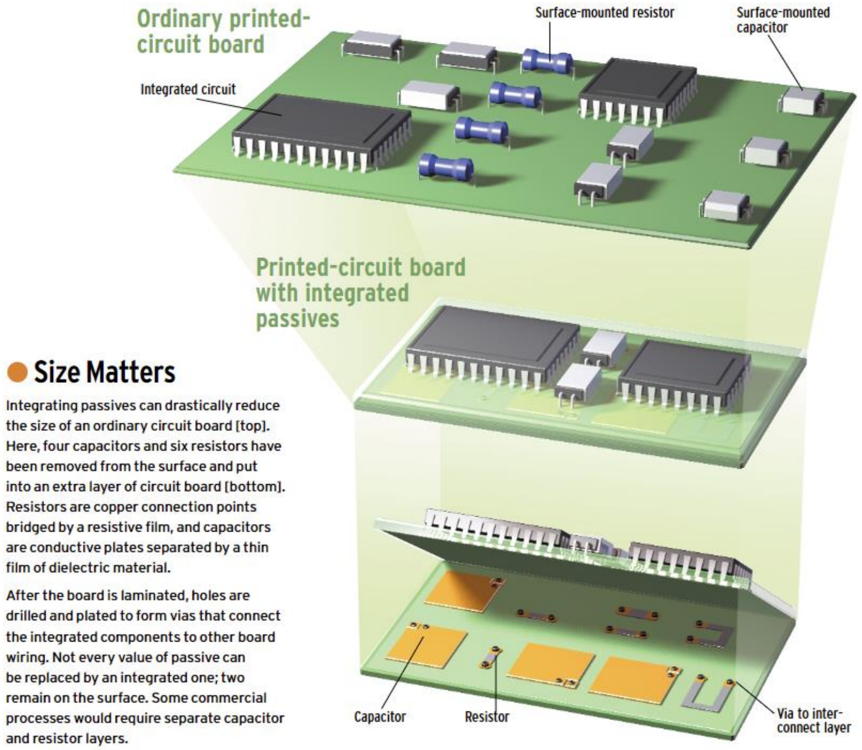
Serpentine-shaped interconnect

Arch Interconnect



Custom **3D-printed** interconnect bend angle **measurement setup**

PCB Miniaturization by Embedding Passives



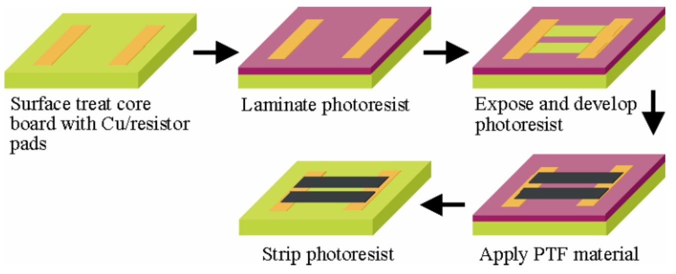


FIG. 4(b). Resistor fabrication process.

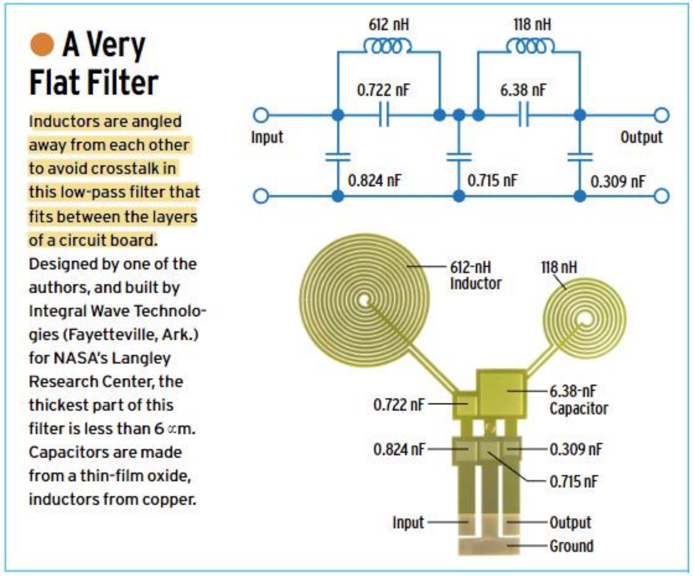
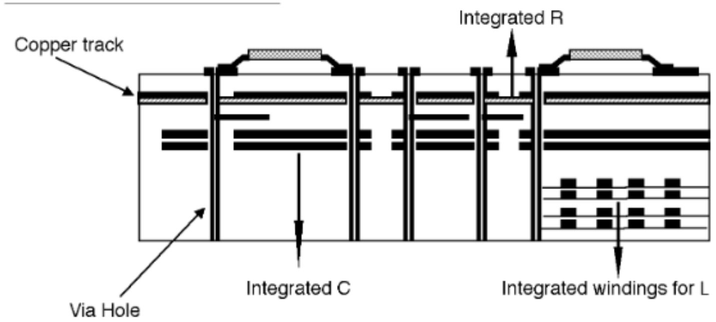


Figure 1
Typical build up of multi-layer embedded passive technology PCB



"In a typical circuit, over **80%** of the electronic components are passives such as resistors, inductors, and capacitors that could take up to almost **50% of the entire printed circuit board area**".

- Passives are integrated within PCB layers using several techniques, including sputtering, plating, CVD, and screen-printing to deposit various film materials.
- **Capacitors**: Require specific materials and process to deposit.
- **Inductors**: Easier to fabricate but raise interference problems

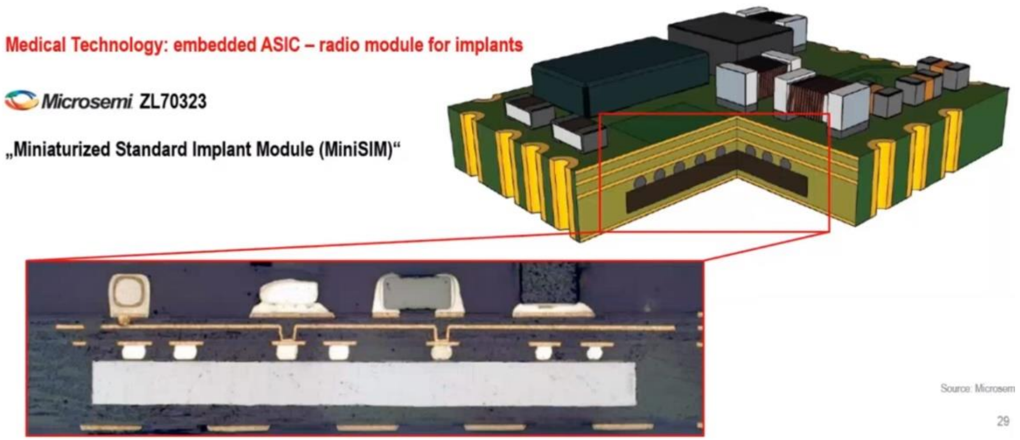
Embedded PCB Components

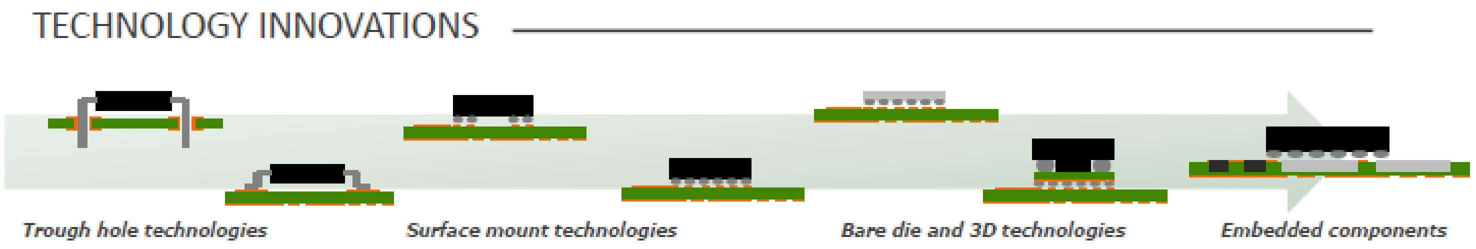
Advantages:

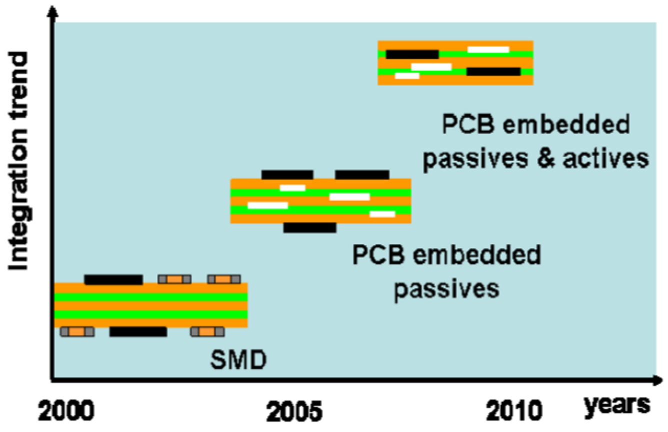
- ✓ Reduction in outer layer surface area.
- ✓ Increased functionality (greater density).
- ✓ Performance improvement (shorter trace lengths).
- ✓ Solving thermal issues (better heat dissipation).

Disadvantages:

- Added cost of getting bare-dies from IC vendors.
- Embedded components can be damaged during assembly.
- Prototype cost is higher.
- Harder to implement using 2D design tools.





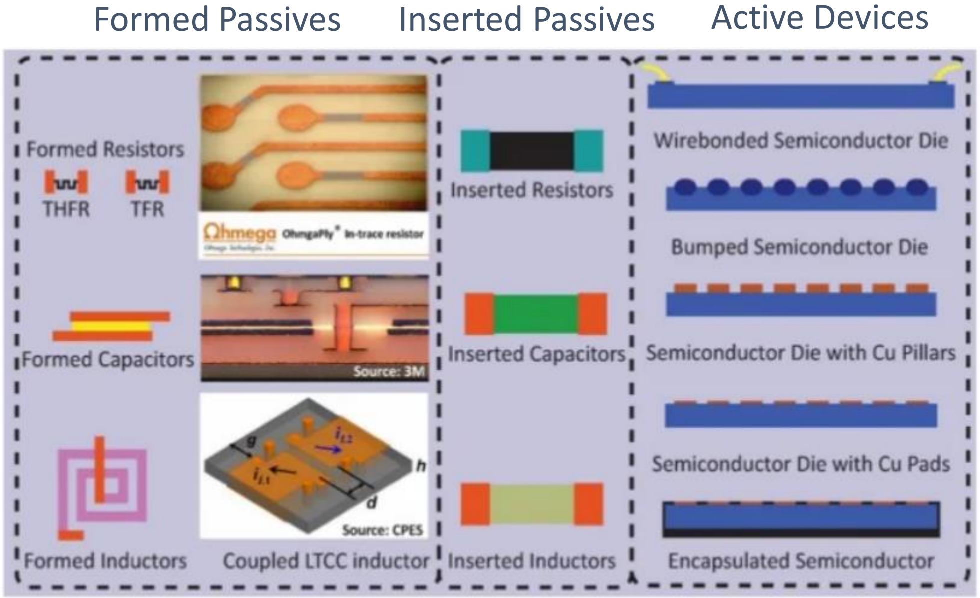


Zuken, Humair Mandavia. n.d. "Implementing Embedded Component from Concept To Manufacturing." *IPC APEX EXPO Conference Proceedings*.

Embedded PCB Components

- **Why is Embedded 3D Packaging Important:**
  - ✓ Reduced size.
  - ✓ Improved performance.
  - ✓ Thermal management.
  - ✓ Reduced packaging.
  - ✓ Ease of use.
  - ✓ Reduce overall cost.
  - ✓ EMI shielding.

Embedded Components



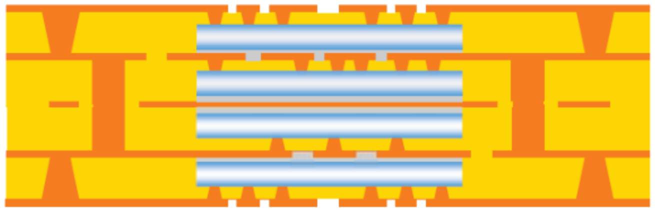


Figure 3: Embedded SiP with four stacked ICs (Image courtesy of FhG-IZM Berlin)

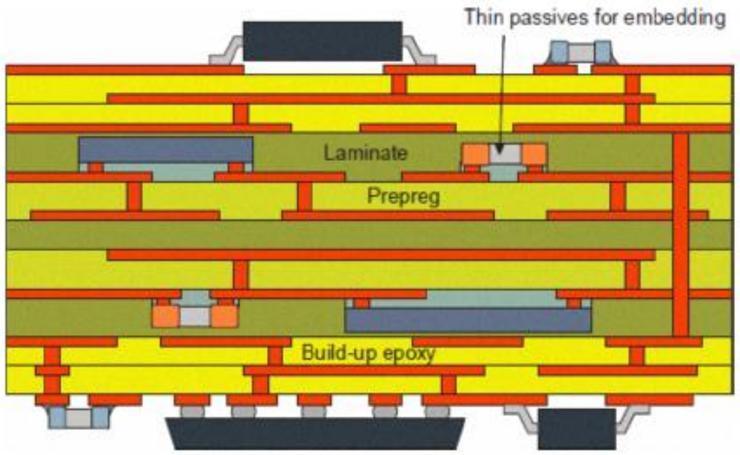


Figure 4: PCB stack-up with two cores dedicated for embedded components

Rigid-Flex RF PCBs as A Mean for Miniaturization

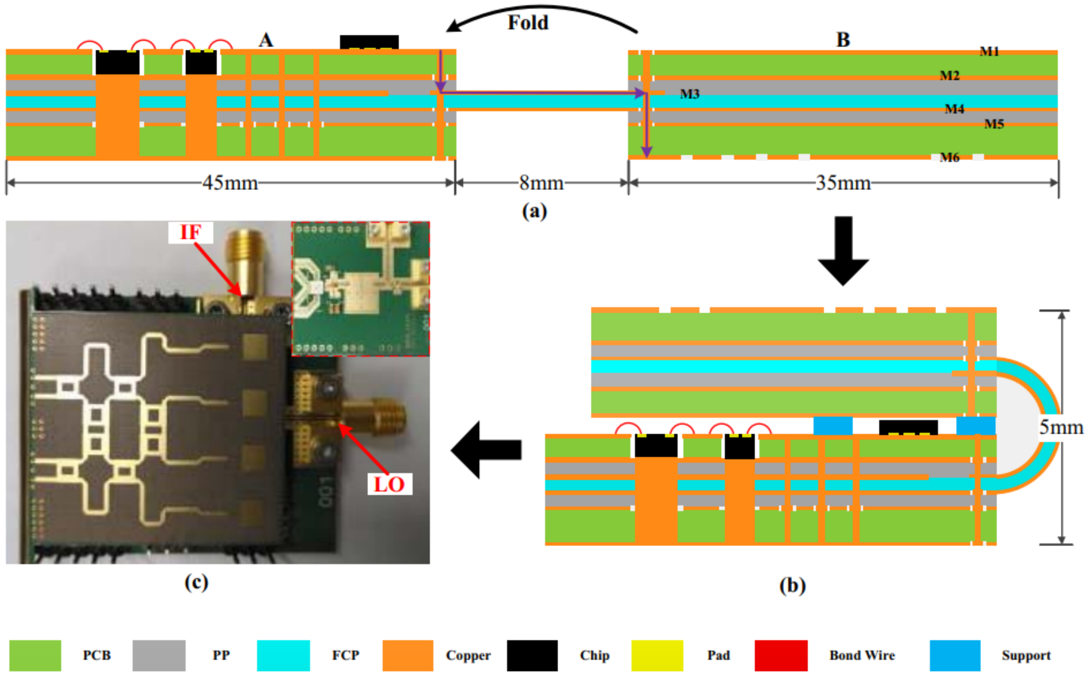


Figure 2. Overall structure of AiP and Manufacturing process.

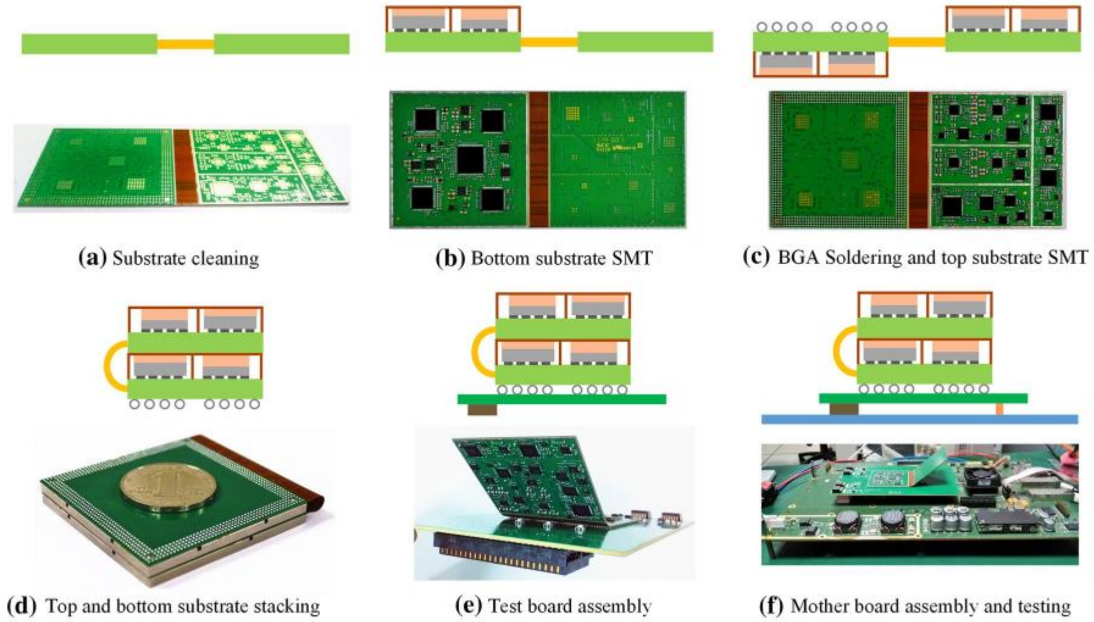
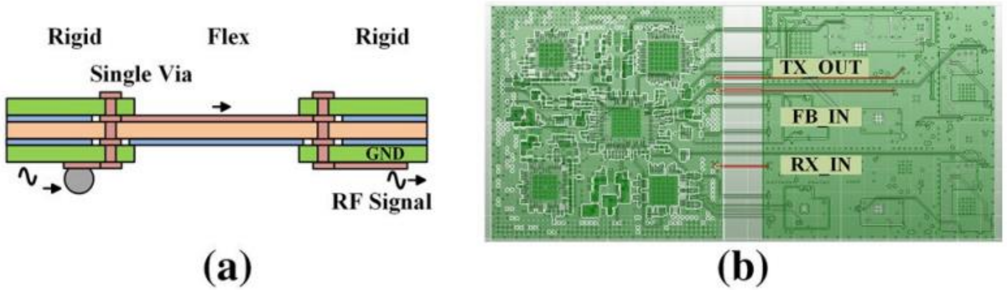
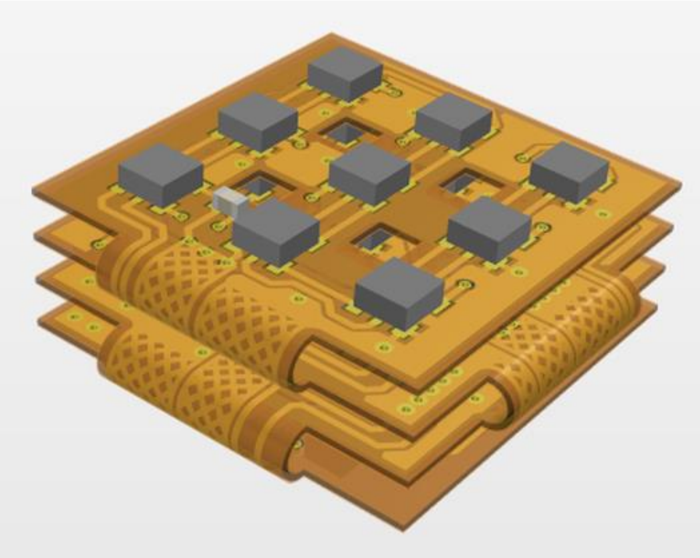
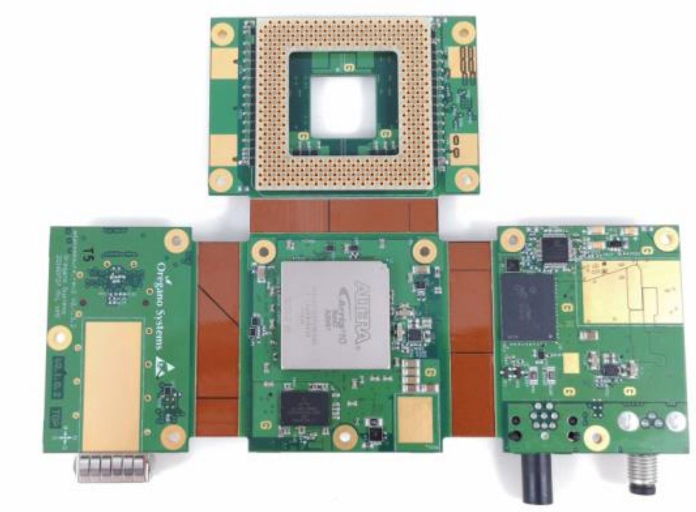


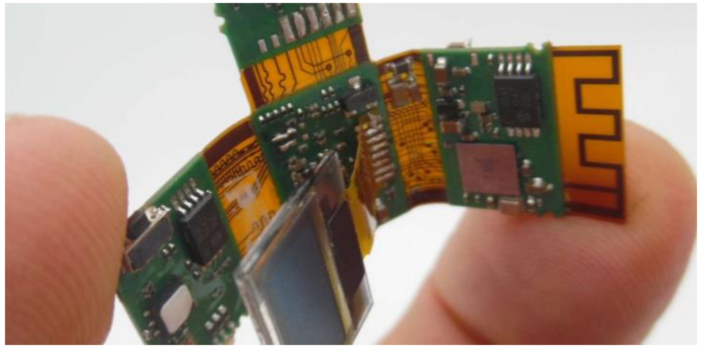
Fig. 4 Packaging and assembly flow of the RF SiP and test system

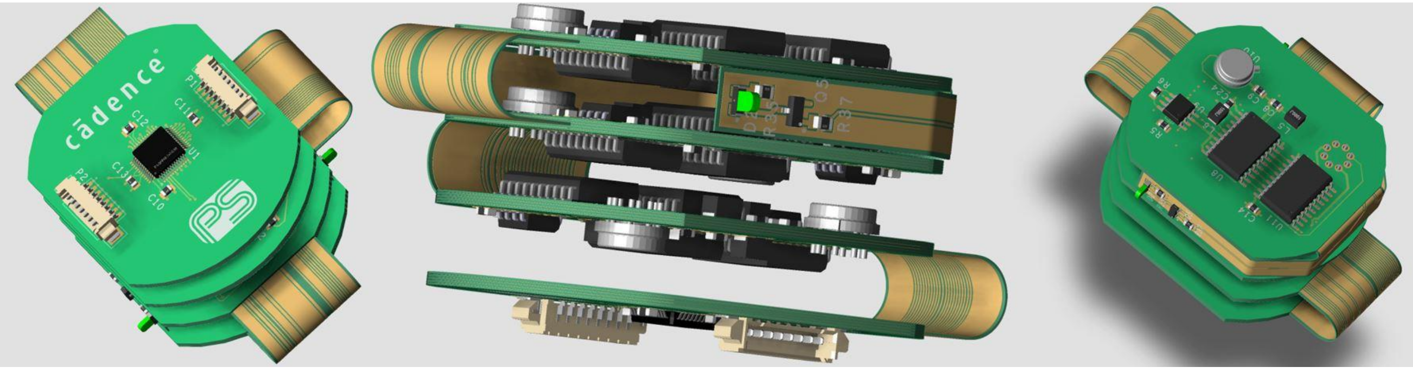


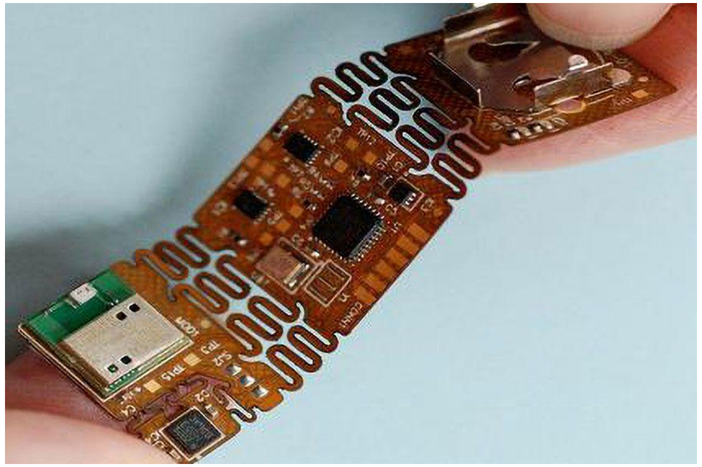
Rigid-Flex RF PCBs as A Mean for Miniaturization





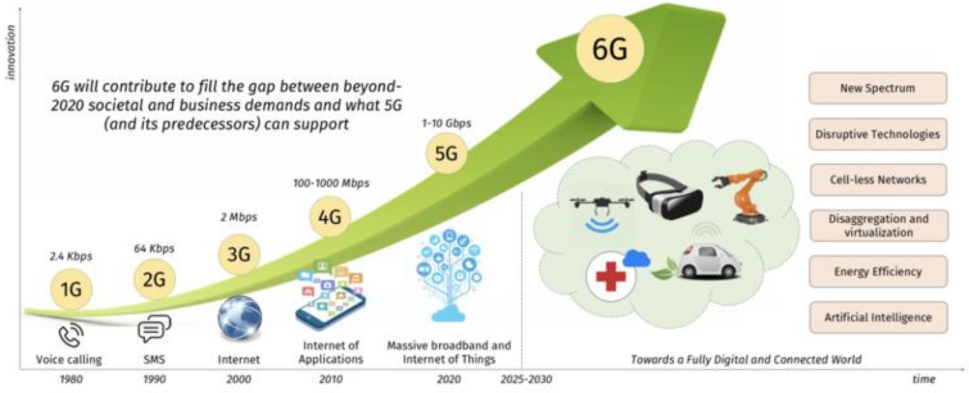


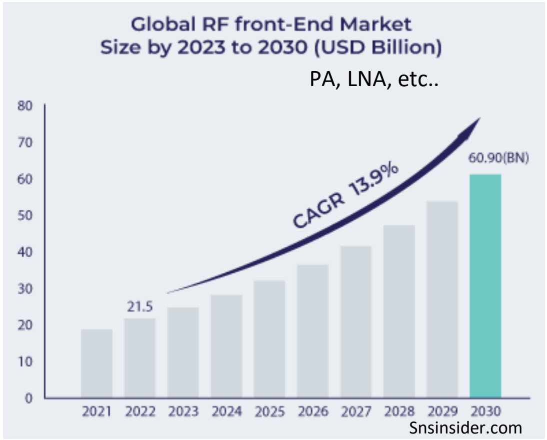




Motivation

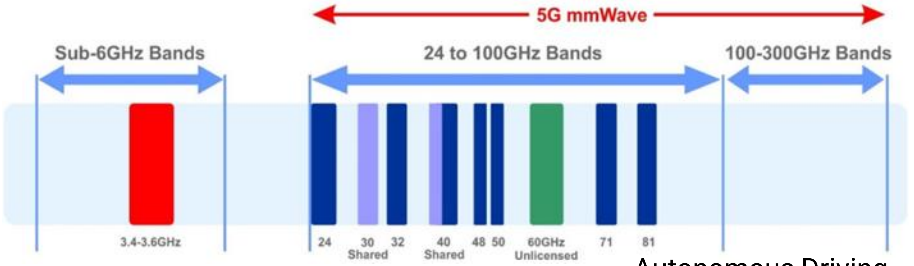
- Every 10 year, a new generation of communication system
- Immense improvement in data rates
- Currently 5G era
- Target for 6G
  100 Gbps
- Emerging areas
  - Wireless Cognition
  - THz Imaging
  - Remote Sensing
  - Information Shower
  - Centimeter Level Positioning
- Need high bandwidth and increasing functionality-->highly integrated, thermal issues-->
- Need Advanced RF Packaging





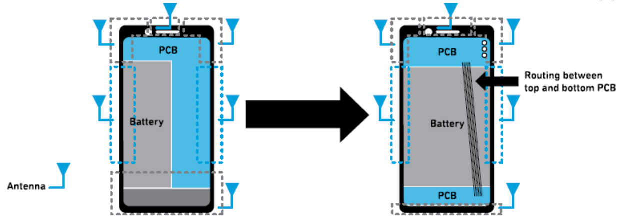
Directivity of mmWave

THz Security Scanning
Video−like scans



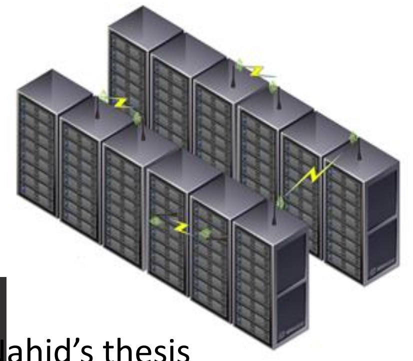
Wireless Data Centers
No cables if wireless speeds can match wired

Autonomous Driving
precise and instant situational awareness



Previous Smartphone　　5G Smartphone

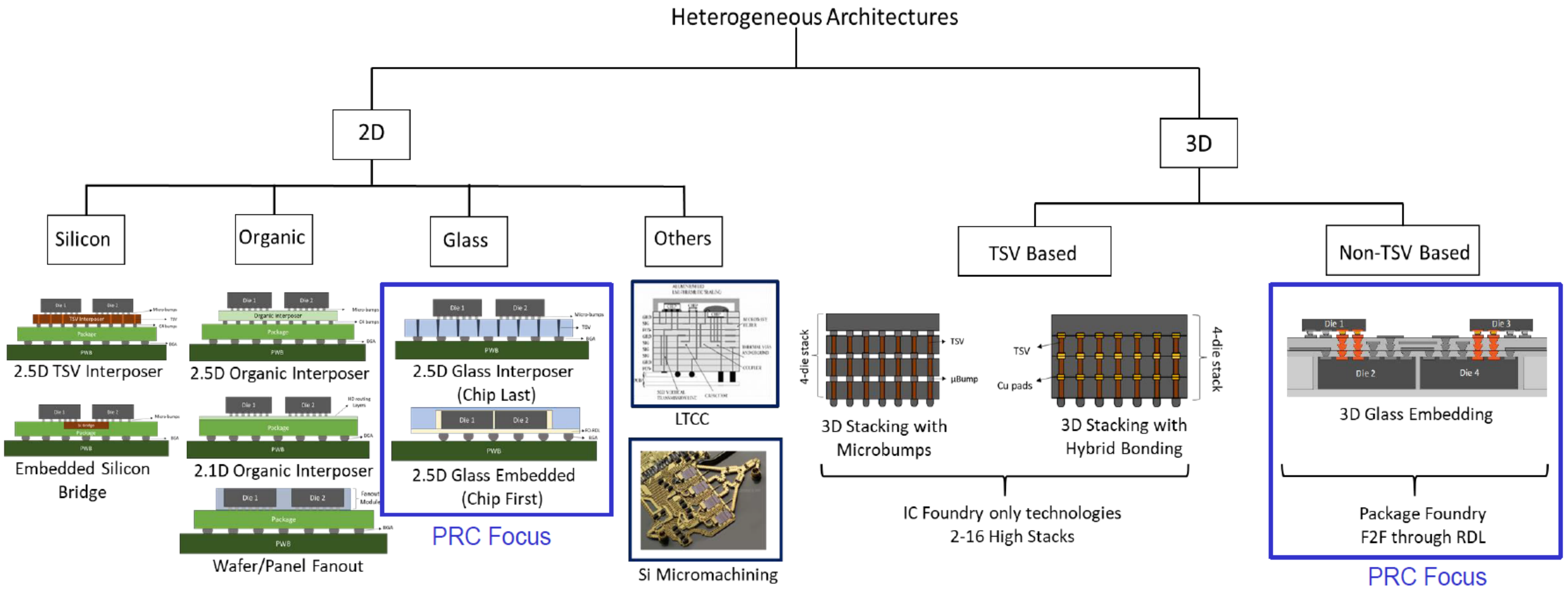
- Larger batteries in 5G phones



[1] http://mmwave.dei.unipd.it/research/6g/
[2] https://www.accton.com/Technology-Brief/the-emergence-of-5g-mmwave/
[3] T. S. Rappaport et al., "Wireless communications and applications above 100 GHz: Opportunities and challenges for 6G and beyond," IEEE Access, vol. 7, pp. 78729–78757, 2019.
[4] D. Schnaufer et al., RF filter technologies for dummies, Qorvo 2nd special edition. Hoboken, N.J.: Wiley, 2022.
[5] DOEEET Blog, (2020) Approaching the 5g mmwave filter challenge, [Online]. Available: https://www.doeeet.com/content/eee-components/rf-mw/approaching-the-5g-mmwave-filter-challenge/\

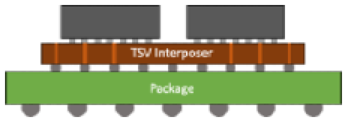
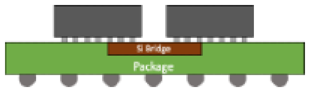
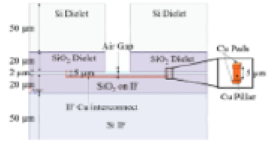
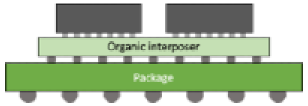
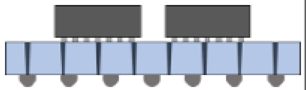
Source; Nahid's thesis

Advanced Packaging & Heterogeneous Integration State of the Art



M. Swaminathan, S. Ravichandran, Heterogeneous Integration for AI Applications: Status and Future Needs (Part 1): Chip Scale Review, Jan-Feb, 2022, p.43. *(Part 2): Chip Scale Review, Mar-Apr, 2022, p-35.*

2D Integration – State of the Art

	2D/2.5D integration					
	Silicon			**Organic**		**Glass Interposer** (*Mukhopadhyay, et al. '19*)
	TSV Interposer (*Martwick, et al, 2016*)	**Si Bridge (EMIB)** (*Mahajan, et al, 2019*)	**Silicon IF** (*Jangam, et al, 2018*)	**Organic Interposer** (*Turner, et al, 18*)	**Chip-last Fanout** (*Wang, et al 2019*)	
						
Status	Commercial	Commercial	Research	Commercial	Development	Research
Dielectric constant	3.9	3.9*	3.9	3.0*	3.2	2.5-3.0
IO pitch	50 μm	45 μm	10 μm	55 μm	40	55 μm
Interconnect length	5 mm	5 mm	0.5 mm	6 mm	1 mm	2.5 mm
Interconnect density	250 IO/mm/layer	300 IO/mm/layer	n/a	25 IO/mm/layer	500 IO/mm/layer	250 IO/mm/layer
V_{swing}	1.2 V	1 V	1 V	0.15 V	1 V	1 V
$R_{on}/C_{Tx}/C_{Rx}$ (Ω/F/F)	39/0.4p/0.4p	50/0.5p/0.5p	30/50f/50f	n/a	50/0.4pF/0.4pF	30/0.3pF/0.3pF
Data rate/IO	2 Gbps	5 Gbps	4.21 Gbps	20 Gbps	9.5 Gbps	9.2 Gbps
Bandwidth density	500 Gbps/mm	1500 Gbps/mm	1300 Gbps/mm	500 Gbps/mm*	4750 Gbps/mm	2300 Gbps/mm
Energy-per-bit	1.025 pJ/bit*	1.2* pJ/bit	0.4 pJ/bit	0.58 pJ/bit	0.78 pJ/bit*	0.36 pJ/bit

** Derived metric*

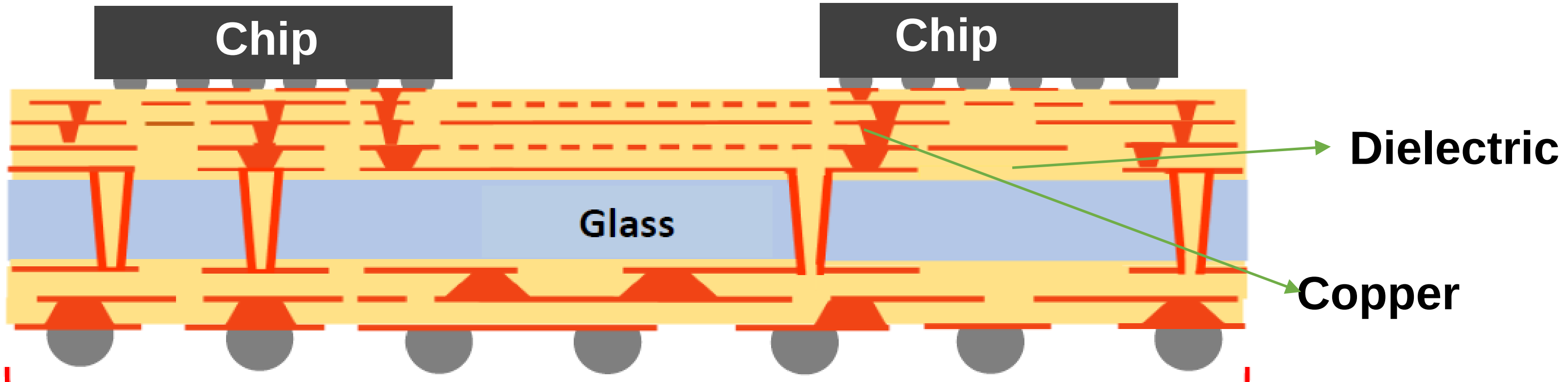
Strategic Need

$$Latency = \tau = RC$$

$$EPB = \frac{P}{f} = \frac{CV^2}{2}$$

Higher Bandwidth Density → Higher I/O density & Data Rates
Lower Latency interconnections → Lower RC
Lower Energy per bit (EPB) → Lower Capacitive losses

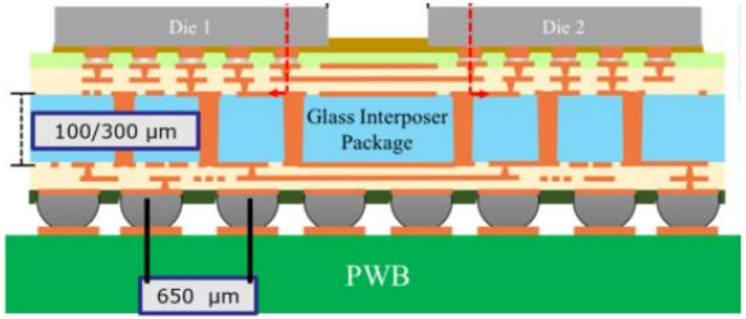
→ Low Dk (< 2.5)



Larger Substrate sizes → Lower stress & warpage → Thinner, Low-stress, Low CTE Dielectrics (< 5 μm)

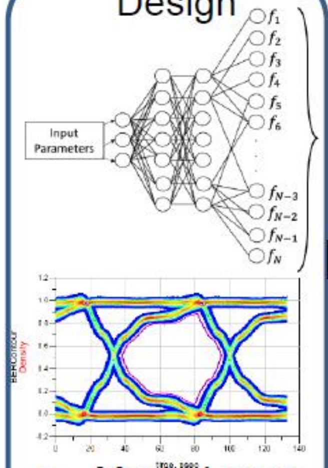
Courtesy: Dr. P. Nimbalkar

AI & High-Performance Computing



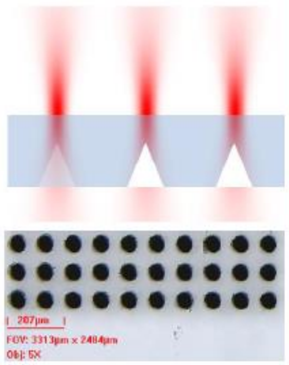
Research Focus Areas **Research Focus Areas**

Design



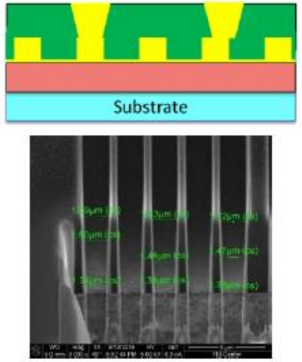
- Mach. Learn
- Optimization

High Aspect Ratio TGV



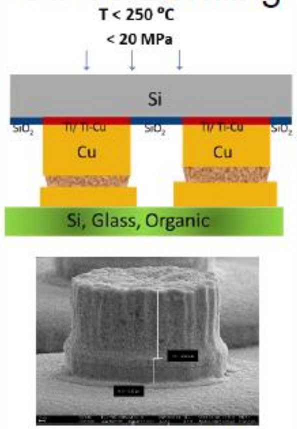
- 300um glass
- 2:1 to 10:1

Panel Scale RDL



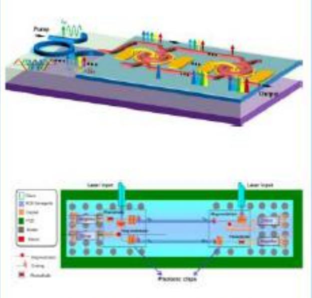
- 1um L/S
- High AR

Cu-Cu Bonding



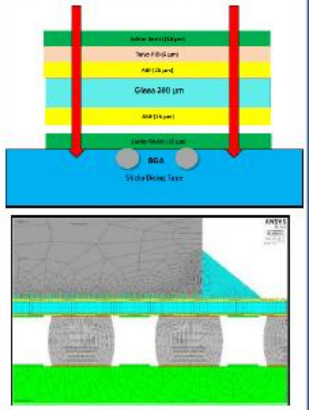
- <20um pitch
- Chip-Substrate

Photonics



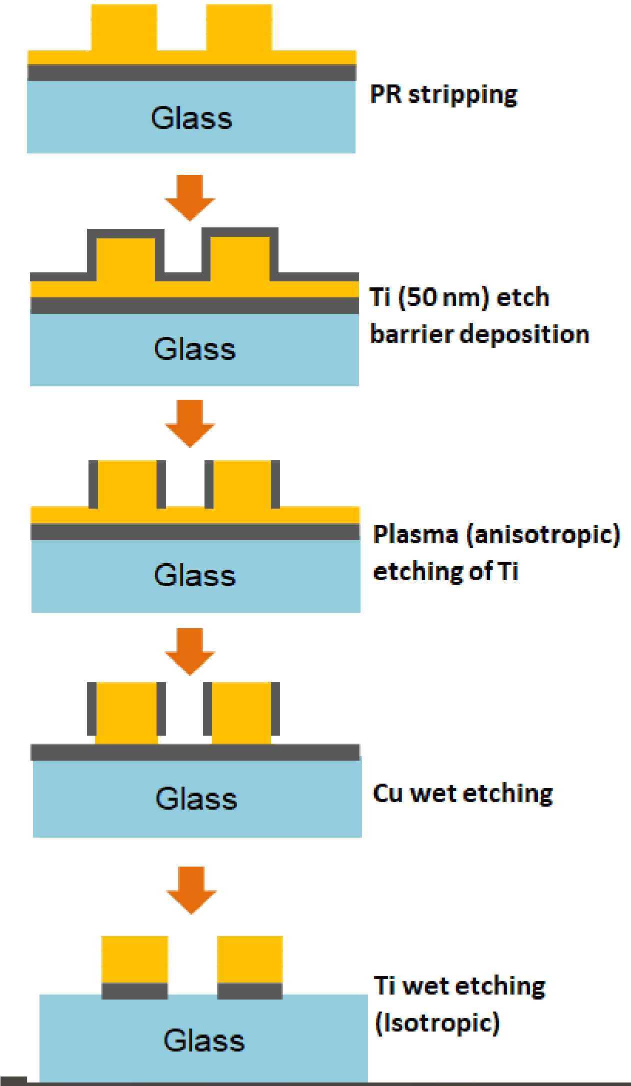
- EPB<1.2pJ/bit
- >900Gbps/lane
- Waveguide
- Coupling

Reliability/Space



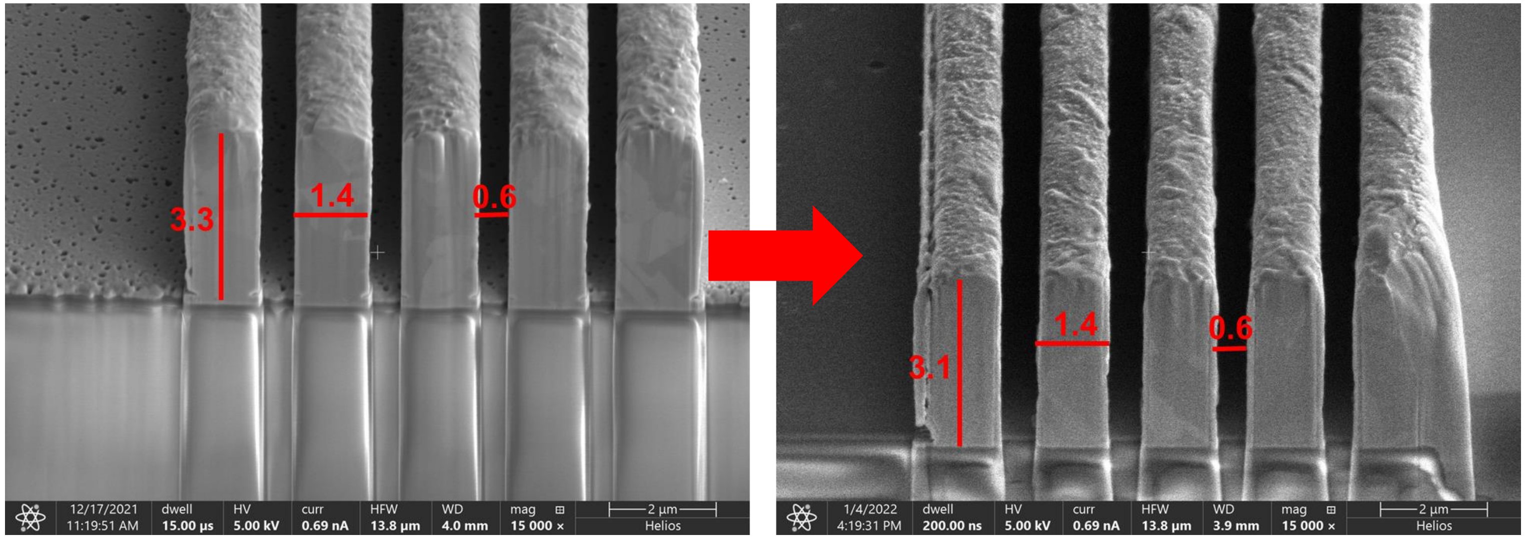
- Large body size
- Double sided

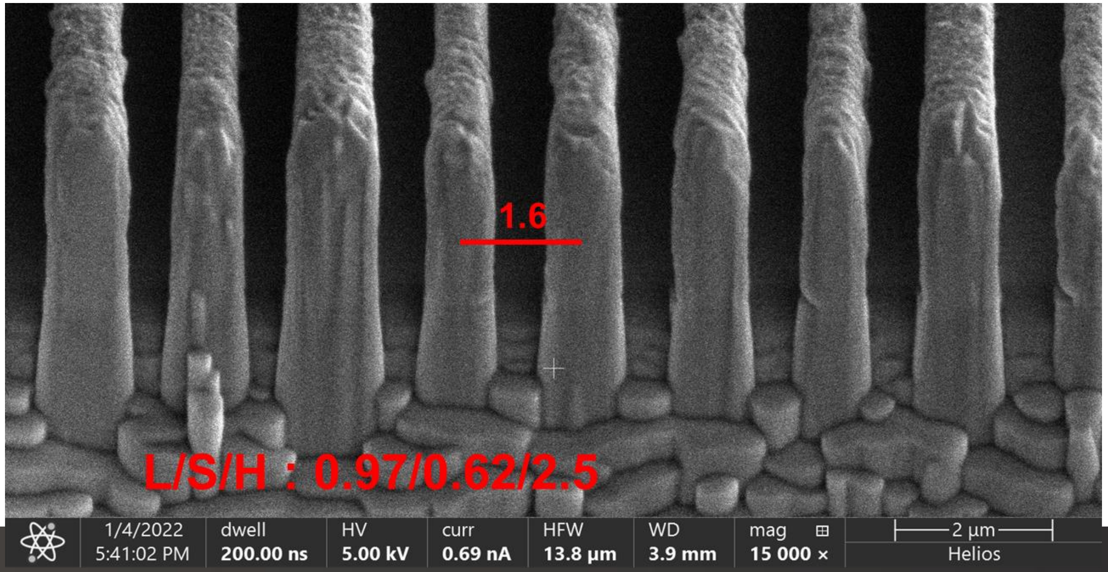
Research Highlights: Novel SAP for <1µm L/S

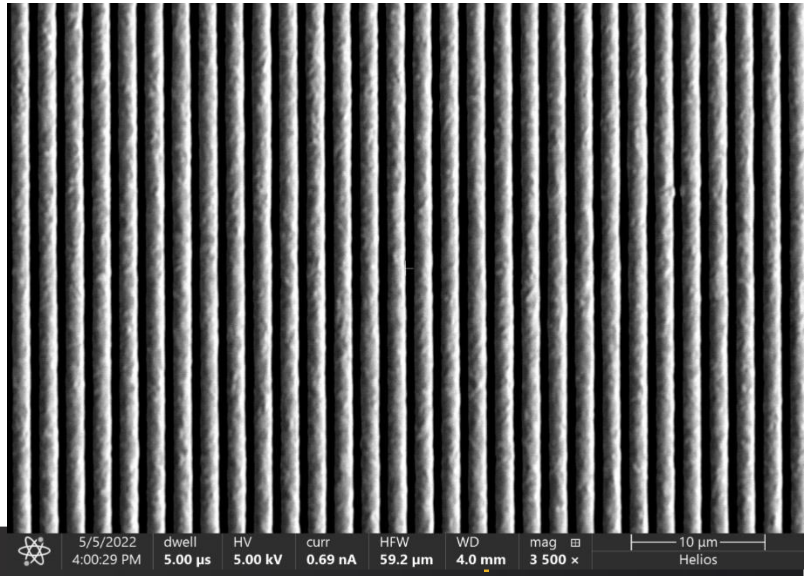


Before Cu etch

After Cu etch



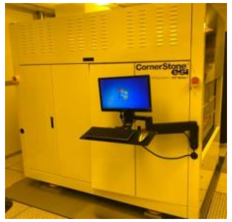




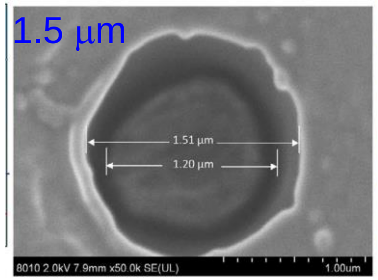
The Other Bottle Neck: Microvia Fabrication Approaches

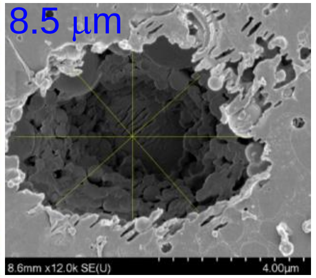
Laser Micromachining

ps UV Laser



fs NIR Laser

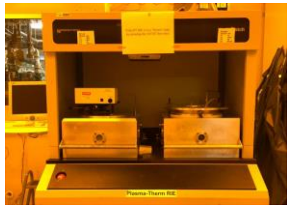


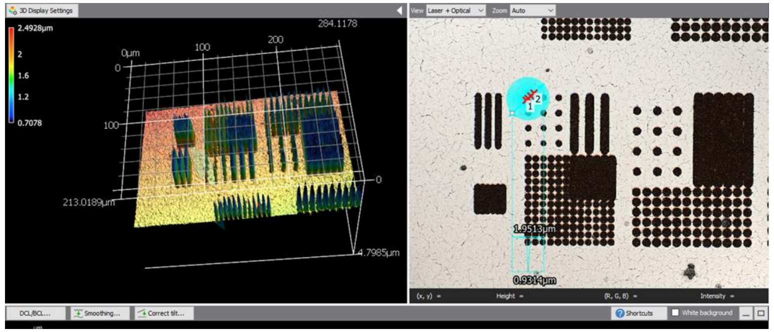


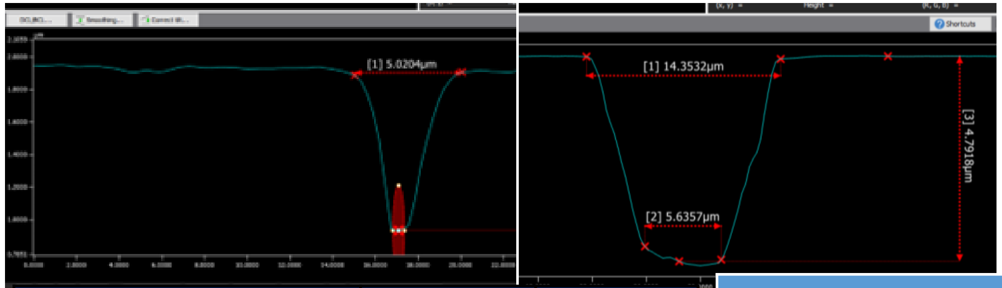
- Via scaling 6-8 µm minimum

Where do we go from here?

Dry Plasma Processes



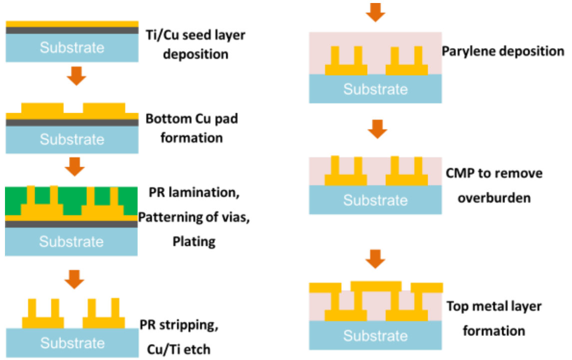




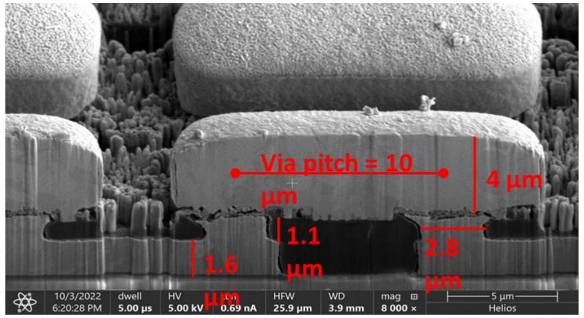
Gas Ratio: CHF_3:O_2	8:2	2:8
Parylene	1.8 µm	2.4 µm
Cytop	2.8 µm	2.8 µm
ABF GX-92P	3.02 µm	1.24 µm

Fully etched 16 µm vias, Partially etched 5 µm vias
Standard RIE processing
Debris formation minimized, but not optimized

Novel Via Formation Processes



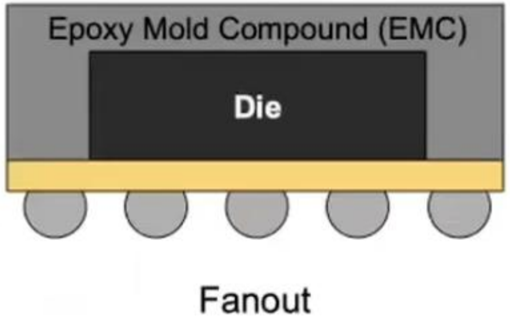
Daisy chain structure for TCT reliability; Via diameter = 2.8 µm; Via height = 1.1 µm

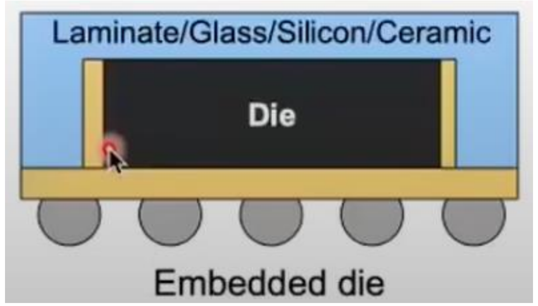


eight but thinned down to 1 µm after planarization
eficial for thermal cycling reliability
ed by better planarization process control
inel-scalable option

Glass in Core Materials for FO/Embedding (HPC-RF)

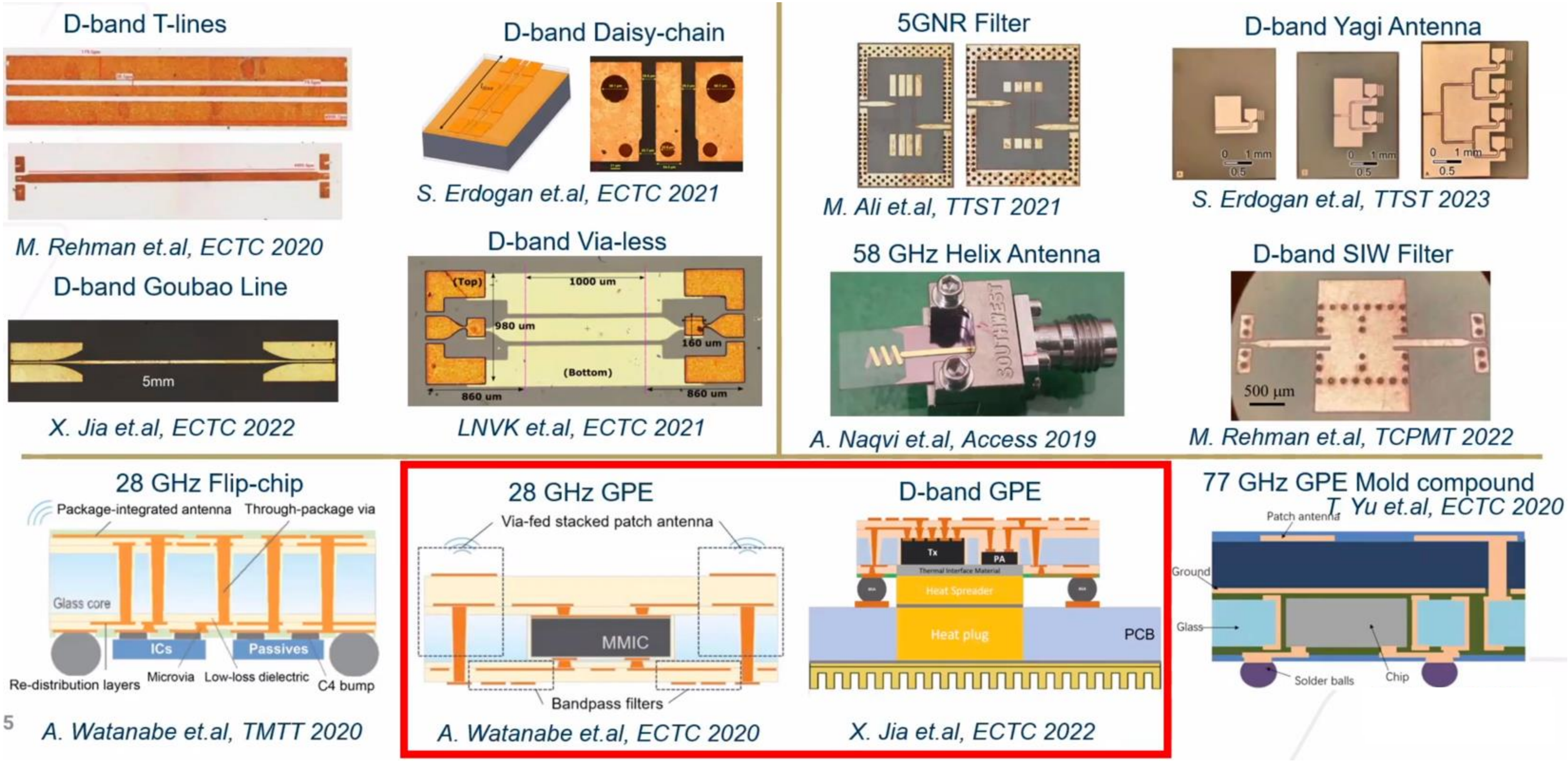
	EMC	OL	Silicon	Glass		Glass	LTCC	Teflon	LCP
Dk	2.8~3.2	2.8~3.2	3.9	2.5~3.2	Dk	2.5~3.2	7.3~8.8	2.1	~2.6 (Dband)
Surface roughness (nm)	>1000	400~600	<1	<1	(nm)	<1	<400		
CTE(ppm/K)	16~30	17	2.9~4	3~9	(ppm/K)	3~9	5~8	120	Controllable but 150 @Z-axis
Young's Modulus (Gpa)	22	10-40	165	50-90	(Gpa)	50-90	150~180	~0.5	Anisotropic
Water uptake (%)	1-2.5%	0.04	0	0	%	0	Hermetic	<0.01	0.01~0.1
Thermal conductivity	0.5-0.75	0.9	148	1.1	W/mK	1.1	~3	~0.2	0.35
	HPC Package Parameters				//RF//				
Interconnect Density (IO/mm/layer)	125	300	125	500	Ins Loss (dB/mm)	0.21~0.28	Low loss	0.3 (110GHz)	0.18~0.33 (110-170GHz)
Package size (mm)	20 x 20	70 x 70	20 x 20	100 x 100	Advantage	Fine feature	Robust	Near hermetic	Low cost, near hermetic
Substrate thickness	Thinning	# Layers, Warpage	Thinning	Heandling	Remarks		Bulky, High Proc. T, Cost, small size, large feature size(due to alignment and printing)	Adhesion, cost,	Rough-requiring polishing, >10um feature size
Reliability	Warpage	Warpage	Warpage	CTE tailored					
Panel/Wafer size (mm^2)	500	710	500	710					





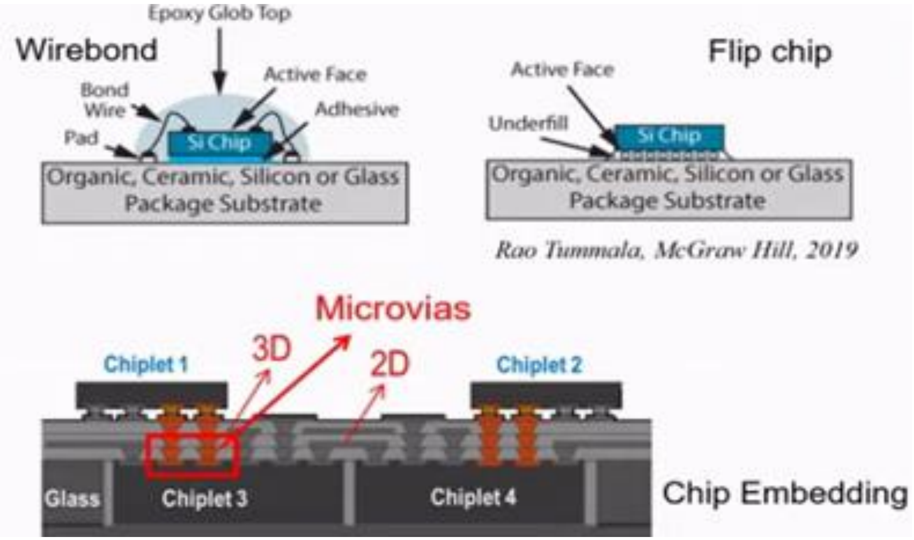
EMC; epoxy molding compound
OL; organic lamination

Glass interposer and RF characterizations in PRC

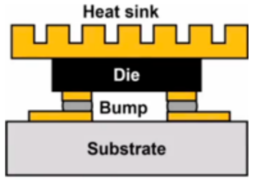


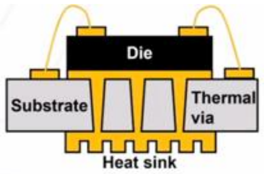
Source; X. Li’s proposal

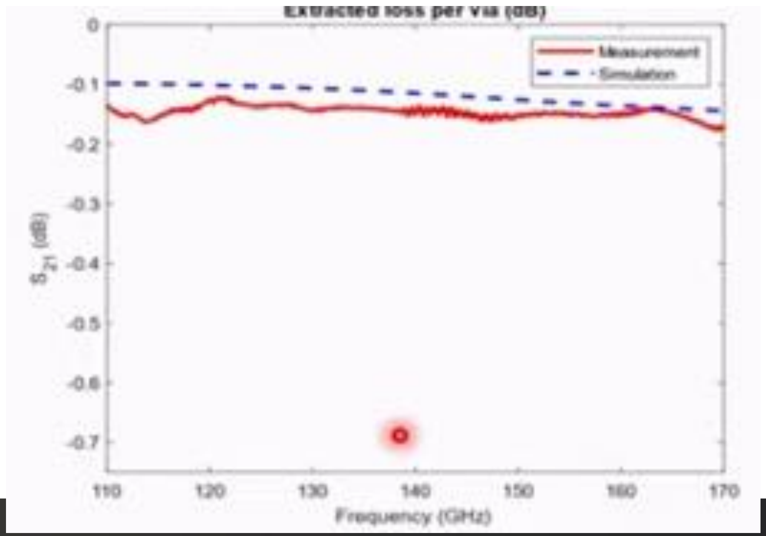
Embedding from Reducing Assembly Loss Parasitics



	Material	Interconnect type	Loss per interconnect
PRC	ABF GL-102	Microvia	0.145 dB140 GHz 0.177 dB @ 170 GHz
Ref1	LTCC	Flip-chip	0.3 dB @ 165 GHz
Ref2	Astra MT77	Flip-chip	0.3 dB
Ref3	Astra MT77	Wirebonding	1.8 dB @ 140 GHz







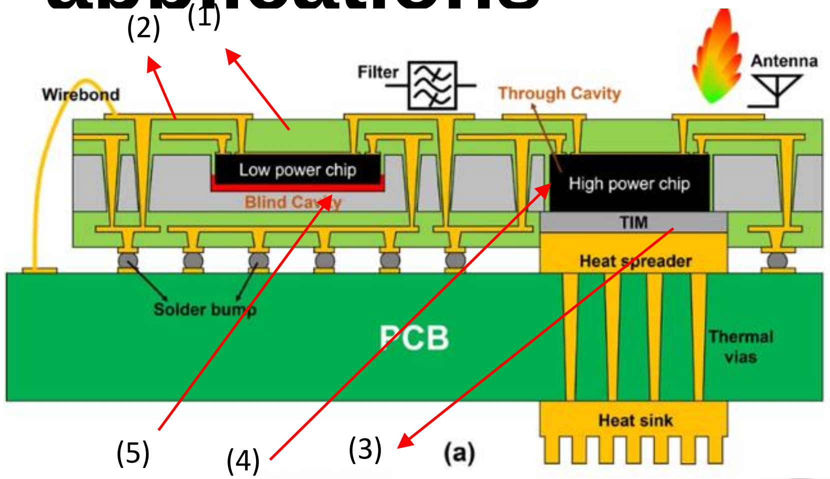
- ❖ □Chip embedding enables RDL to Chip loss reduction!
- ❖ □~0.15dB lower than Flip chip @ 140GHz
- ❖ 1.65dB lower than Wirebond

Serhat et al, ECTC 2021

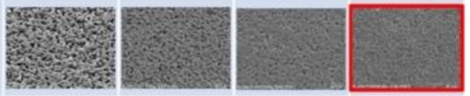
Challenges in GPE packaging in RF applications

- Implementation of well-structured interconnections
  - Low **loss**, Impedance matching, parasitic-reduced design (Chip2Chip, Chip2Passives and Passives2Passives)→**RDL**, low loss **dielectric** (1) , smooth **transmission line** (2), and low CTE/warpage
  - Loss=$L_{dielectric}(\sqrt{\varepsilon_r} \times \tan\delta \times f)$ + $L_{conductor}$(skin effect/depth + scattering/roughness)
- Thermal management
  - PA chip→ heat dissipation with high K TIM (3)
- Process compatibility
  - Mechanical integrity and reliability from materials and stack-up structures → filling (4), carrier, TR tapes, DAF/blind cavity (5)
  - Singulation in thick dielectric (low C, RF gain) (5)
- Reliability ?

(5)

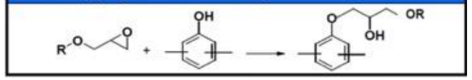


New

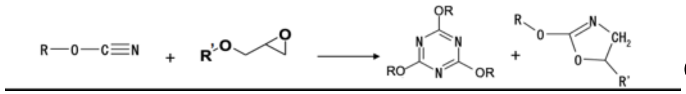
ABF	GX92	GXT31	GZ41	GL
CTE (ppm/K) 30-150deg.C	39	23	20	20
Tg (deg.C, DMA)	168	172	198	171
DK (5.8GHz)	3.2	3.4	3.3	3.3
Df (5.8GHz)	0.018	0.014	0.0074	0.0044
Surface Image (SEM, x 3,500)				

Source: Ajinomoto Fine-Techno Co..

GX series (Epoxy & Phenol Hardener)

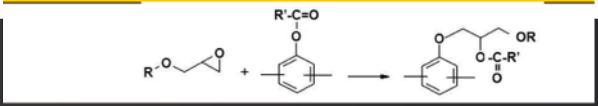


GZ series (Cyanate ester & Epoxy)



Cyanurate ring

GY series (Epoxy & Phenolic Ester Hardener)



Comparison with other works

Multi-chip embedded glass interposer

Ref.	Substrate Type	Chip Assembly	Interconnection	Frequency	Loss (dB/transition)
W. -C. Wu et al.	Alumina & GaAs	Flip-chip	Microstrip to CPW and hot via	DC – 67 GHz	0.32 @ 40 GHz, 0.5 @ 67 GHz
T. Zheng et al.	Fused silica	Stitch chip	Compressible interconnect and CPW	DC – 40 GHz	0.2 @ 28 GHz, 0.2 @ 39 GHz
W. -M. Wu et al.	Silicon & Glass	Beside the carrier	Three-path bondwire	DC – 92 GHz	< 3dB @ 92 GHz
J. A. Qayyum et al.	Polyimide	Taped on carrier	Aerosol jet printed CPW	DC – 30 GHz	0.27 @ 30 GHz
S. Sinha et al.	Silicon AlN and BCB	Flip-chip	Back-to-back multilayer strip-line and vias	DC – 300 GHz	< 0.9 @ 500 GHz
A. O. Watanabe et al.	Glass & ABF	Flip-chip	Electrolytic plated transmission line and through-package vias	22 GHz – 30 GHz	0.4 @ 24.5 GHz, 0.5 @ 29 GHz
This work	**Glass & ABF**	**Embedded die**	**Electrolytic plated microstrip line and via transitions**	**40 MHz – 110 GHz**	**< 0.687 @ 80 GHz (Both die)**

Electrical performance

Ref.	Type	Stack-up	Chip Assembly	Body size (mm)	Thickness (μm)	Test Tool/Condition	Warpage (μm)
V. Jayaram et al.	Organic interposer	ABF/Organic /ABF	No die	L = W = 17 (Panel)	30 (ABF) 200 (Organic)	Shadow Moiré/70°C stage temperature, 25°C TCB	~40 (0.235%)
M. -K. Shih et al.	Glass interposer	Glass/Chip+ EMC	Flip-chip	D = 203.2 (Wafer)	700 (Glass) 450(EMC)	Advanced Metrology analyzer (aMA)/ 30°C	~1000 (0.492%)
K. Oi et al.	Organic interposer	Organic substrate/Thin film	Flip-chip	L = 21, W = 15 (Panel)	400 (Sub) 260 (Film)	Shadow Moiré/RT	30 (0.143%)
F. X. Che et al.	FOWLP	Dielectric/EMC+chip/Dielectric	Embedded	D = 304.8 (Wafer)	200 (Total)	Fogale T-MAP Dual 3D IR microscopy/RT	~3000 (0.984%)
T. Funaki et al.	Chip-on-wafer integration	Basewafer/Wafer+ chip/Mold	Embedded	D = 300 (Wafer)	775 (B-wafer) 100 (Mold)	N.A./N.A.	800 (0.267%)
This work	**Die-embedded glass interposer**	**ABF/Glass+ Chip/ABF**	**Embedded**	**L = W = 76.2 (Panel)**	**60 (ABF) 150 (Glass)**	Shadow Moiré/65°C	**260 (0.341%)**

Panel warpage

SR: Solder resist
TCB: Thermocompression bonding
RT: room temperature

👍 Wideband, low-loss, controllable warpage and thermal management solution integrated

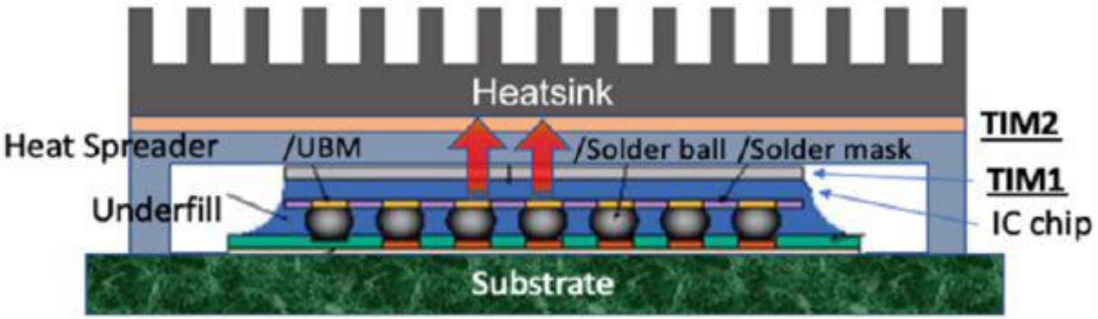
TIM/Die attach-SoA

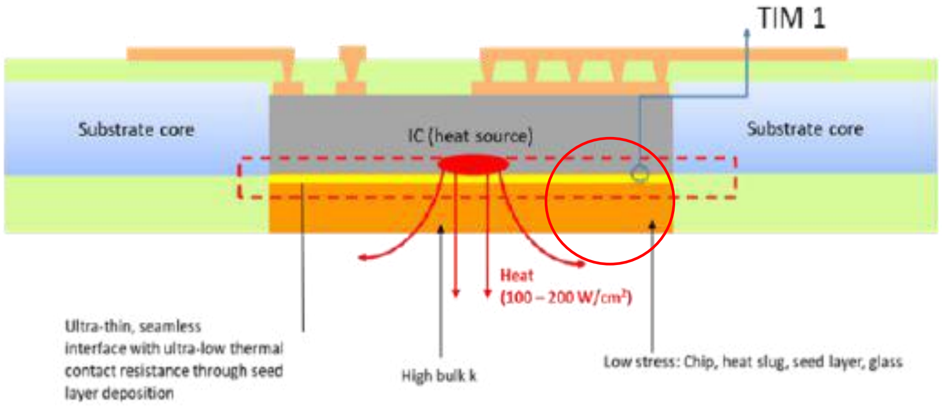
	Grease	PCM	Gels	Ag/Cu polymer pastes	Sintering Ag, Cu etc.	Reflow soldering (In alloys, SAC, etc.)	Liquid metal (GaInSn etc.)
K_{TIM} (W/mK) or R_{TIM} (cm^2/W)	~0.1 [R]	~0.1 [R]	~0.1 [R]	~60~70 [K]	>300 [K]	> 80[K]	~70 [K]
Benefit	Thin BLT, low viscosity to fill, high K	No cure, high viscosity for stability	Conformal	Conformal, Low temp, No surface finish needed, Acceptable shear	Lead-free, high K Ag; ambient Cu; low cost, organic/grp coating, Shear strength	High K, Reworkable,	Wet on various surfaces (glass, organic, metals)
Known issues/risks	Phase separation, messy (migration)	Low K, need pressure	Cure, lower adhesion	Limited K Engineering surface modifications	Pressure helps cost, porosity control, time, temperature, inert (Cu)	Short fatigue life (SAC), interfacial failures due to brittle IMC	To confine its shape, corrosive to metals (exp. W and Ta) Need to confine
Comment	Silicone based K fillers	Polyolefin , acrylics, with BN or alumina	High K filled gel to be cured	**Ag semi-sinter paste** (sintered metal network with polymer binder)	Metallic	Metallic, used in CPUs	Used PS5, AMD SiP

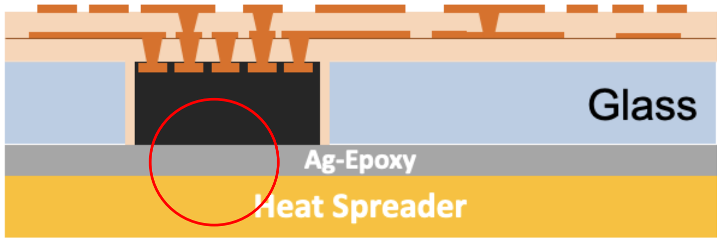
❖ sp2 carbons- VACNT, graphene being explored

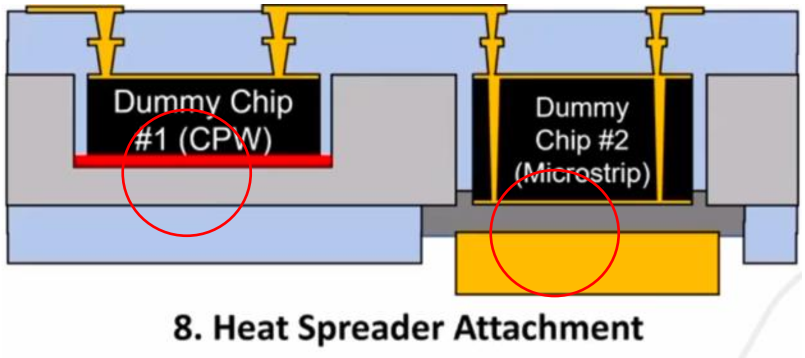
Thermal management

- To reduce thermal resistance at interfaces









TIM in Flip-chip and TIM/DAF embedded package

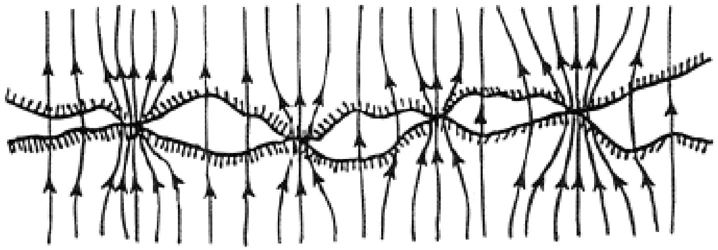
M. Swaminathan, et al., MRS, 2022

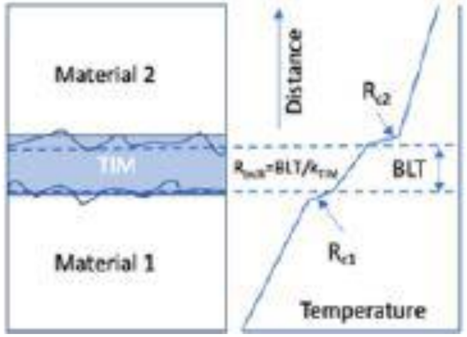
Thermal interface materials (TIM)

Material property
Laser flash

Considering interfaces

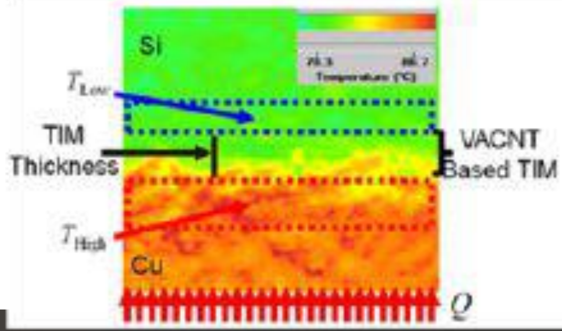
Std thermal impedance measurements





$$R_{\mathrm{TIM}} = \frac{\mathrm{BLT}}{k_{\mathrm{TIM}}} + R_{c1} + R_{c2}$$

$$\alpha = \frac{k}{\rho C_p}$$



IR microscopy

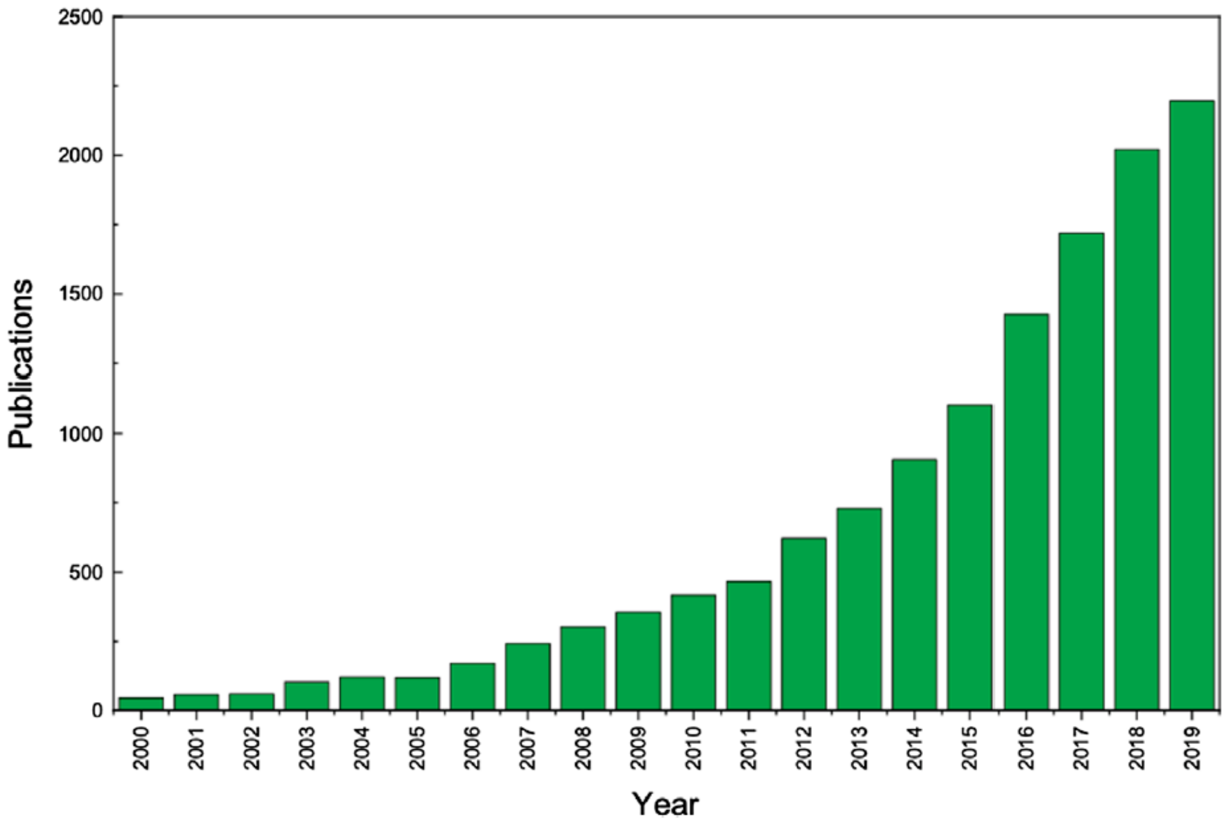
TIM is introduced to fill air pockets of interfaces

 Thermal diffusivity, specific heat, density and thermal conductivity

Printed Flexible Electronics

Increasing demand for flexible electronics for:

1. Wearables.
2. Textile electronics.
3. Biomonnitoring and sensing.
4. Low-cost applications.
5. Disposable and environmentally friendly.
6. Light weight and conformal sensors for robots and aircrafts.



Research publications for the term "**Flexible Electronics**"

Corzo, et. al. (2020), doi: 10.3389/felec.2020.594003

6G Terminology

November 12, 2023 at 12:39 PM

BCI: brain computer interface

DLT devices: distributed ledger technologies (along with blockchain: next generation distributed sensing services whose need of connectivity will require a mix of URLLC and mMTC)

AR/XR/VR augmented/mixed/virtual reality

CRAS connected robotics and autonomous systems

XR extended reality

MBRLLC mobile broadband reliable low latency communications

mURLLC massive URLLC (URLLC+eMBB)
HCS human centric services
MPS multipurpose 3CLS (convergence of communication, computing, control, localization and sensing) and energy services

eMBB: 5G enhanced mobile broadband (eMBB) is the first 5G category to bring the benefits of 5G to the general public. 5G eMBB delivers high-quality internet access even under harsh environmental conditions. 5G eMBB guarantees gigabit range of mobile broadband speeds and higher data bandwidth.

- End-to-end latency between the device and base station – around 5 milliseconds
- 99.99% reliability
- End-to-end data security

URLLC ultra reliable low latency communications for autonomous vehicle networks (below 4msec range)

mMTC massive machine type communications
The service category called massive machine-type communication (mMTC) supports massive device connectivity in IoT applications. 5G mMTC uses non-human-type communication models that prioritize low-rate, uplink-centric transmission. There are no collisions in 5G mMTC use case applications, as the schemes are different from the ones used in traditional human-type communication. 5G mMTC use cases utilize small packet data transmission techniques. 5G mMTC also combines random access and scheduling strategies when there are thousands of IoT devices waiting for access.

VLC: visible light communication (400-800 THz) for ubiquitous computing / fluorescent 10kbit/sec, LED 500Mbit/sec short distances)

LIS: large intelligent surfaces

OAM-MDM orbital angular momentum mode division multiplexing

SON (self-organizing networks) to SSN (self-sustaining networks)