# 6G Hardware System Design and Packaging Needs

P M Raj, Satheesh Venkatakrishnan, John Volakis
Florida International University
Miami

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Advancing manufacturing technology

# Markondeya Raj Pulugurtha (P M Raj)

Associate Professor, FIU (in BME and ECE Departments)

- 20 years of experience in power, RF/mmWave and sensor packaging
- Expertise in passive components, 3D package integration, wireless biosensors
- 360 publications, which include 8 patents.
- More than 25 best-paper awards.
- Co-advised ~40 MS and PhD students
- Former Chair of Nanopackaging Technical Committee, Former EPS Representative of IEEE Nanotechnology Council, IEEE Distinguished Lecturer in Nanotechnology for 2020-2021, Associate Editor for IEEE Nanotechnology Magazine and Transactions of Components, Packaging and Manufacturing Technologies (T-CPMT), General Chair for 3D PEIM 2023
- PhD from Rutgers University in 1999 in Ceramic Engineering,
- ME from the Indian Institute of Science, Bangalore
- BS from the Indian Institute of Technology, Kanpur (1993)



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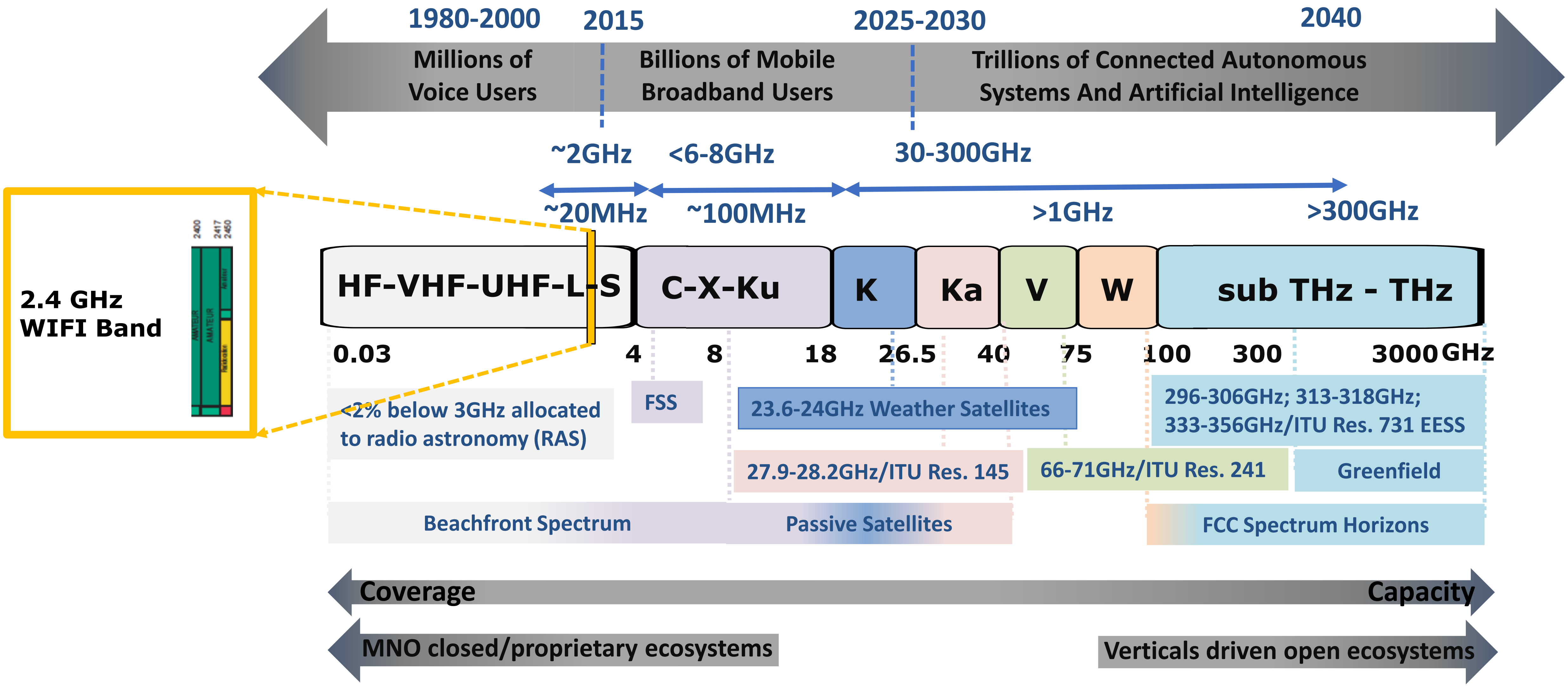
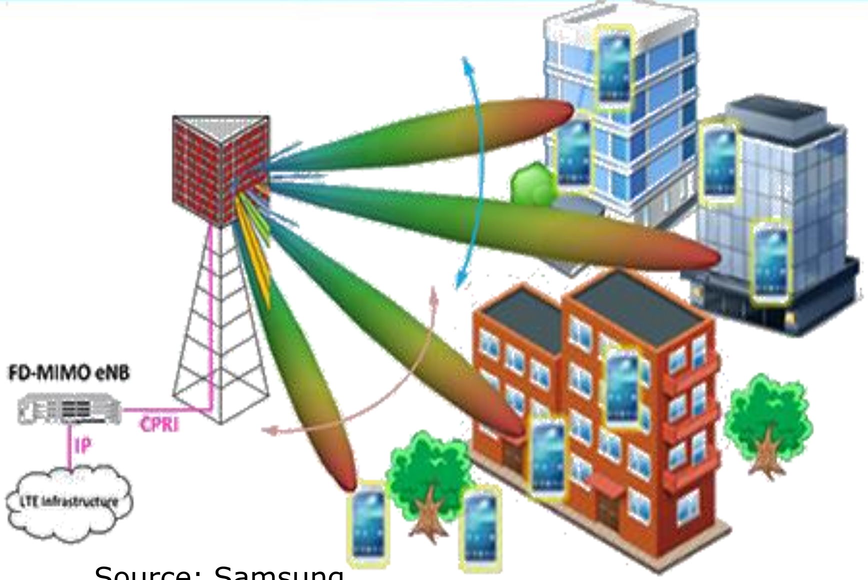
# Outline

- Beamforming Architectures
- Reconfigurable intelligent surfaces
- Package Integration Trends
  - Antenna-in-package
  - Embedded filters, power dividers
  - Tunable FSS

# Spectrum Sharing Evolution



# Research Areas in 5G, 6G, and Beyond



Source: Samsung


Source: https://www.extremetech.com/extreme/176093-v2v-what-are-vehicle-to-vehicle-communications-and-how-does-it-work

New Market Demands

Amazingly Fast
Great Service in a crowd
Super Real-time & reliable communications
Ubiquitous "things" Communicating

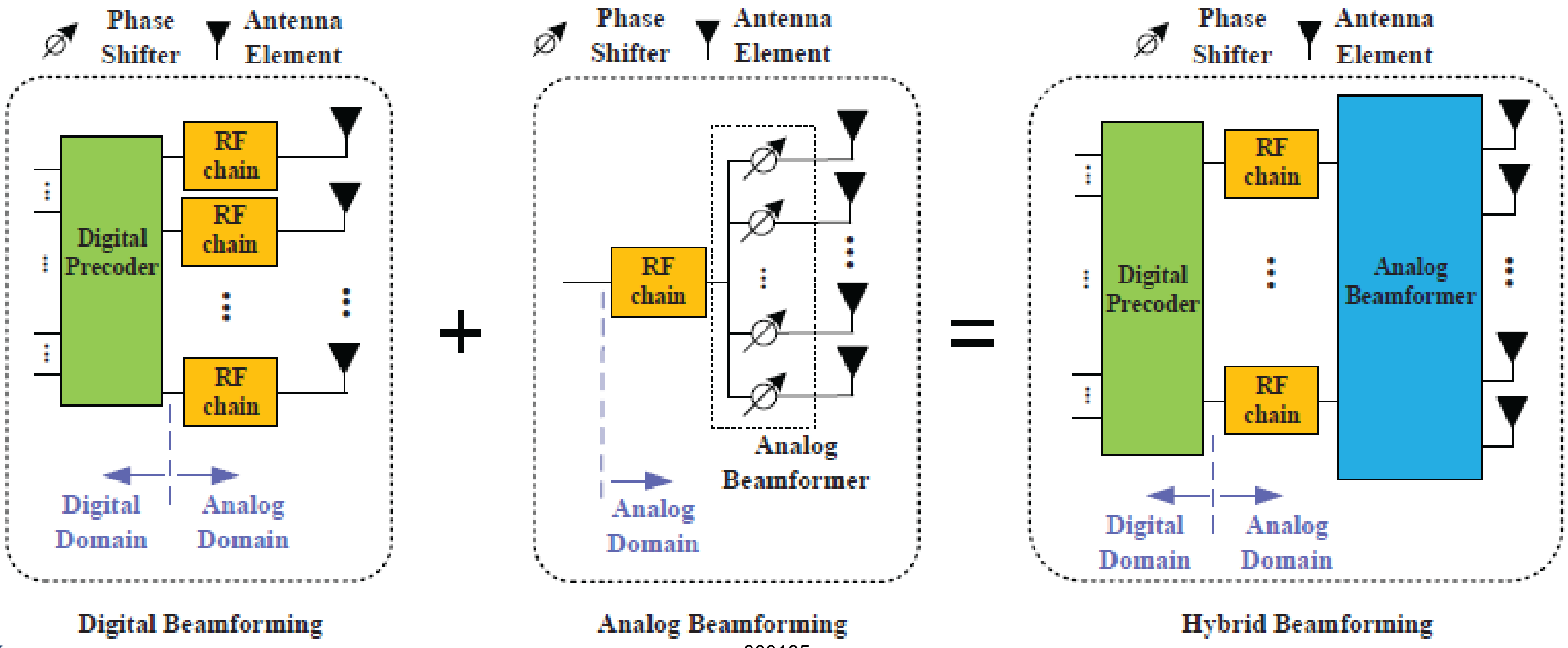
**Areas of Research:**

***1) MIMO beamforming architectures***
***2) Advanced techniques to address spectrum coexistence and improve spectral efficiency and interference mitigation***
3) Ultra-Wideband (UWB) systems
4) RF front ends: frequency agile, very small size, weight area, and power efficient (SWAP)
5) SMART Antennas
6) Millimeter-wave systems
7) RF-digital Transceivers
8) Integrating Machine Learning and Artificial Intelligence in RF design
9) Communication in contested environment

# R1: Beamforming Transceiver Architectures

**Analog beamforming:**
- Antenna phase is adjusted through the phase shifters in the analog domain
- Limits flexibility of control and impairs the beamforming performance and capacity improvement

**Digital beamforming:**
- Realizes any linear transformation of multiple signal streams from the digital baseband to the antenna elements
- Provides a greater degree of freedom
- Unaffordable to be applied in massive-MIMO systems due to the high-power consumption and high system cost






[1] Ning, B., Tian, Z., Chen, Z., Han, C., Yuan, J., & Li, S. (2021). Prospective beamforming technologies for ultra-massive MIMO in terahertz communications: A tutorial. *arXiv preprint arXiv:2107.03032*.

# Hybrid Beamforming

Hybrid beamforming methods jointly optimize the analog and digital beamformers to maximize the achievable rate based on cost-performance trade-off.

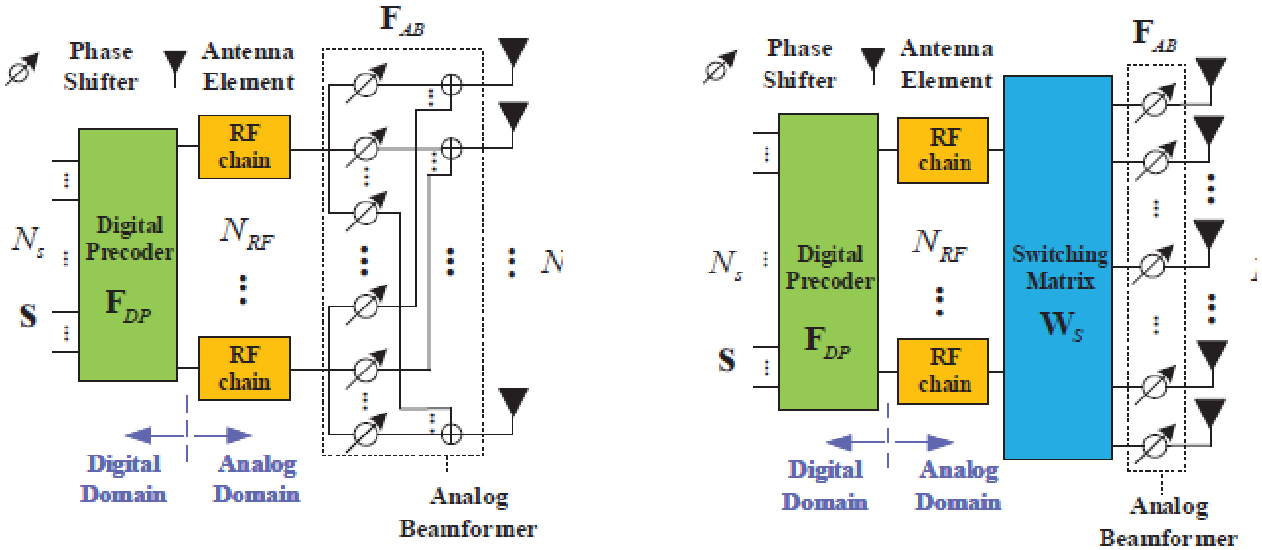



*Fig: Fully-connected vs Dynamically connected HB*[1]

***Advantages***

- Enables mmWave Massive MIMO communications with 1000 × capacity enhancement
- Reduces Capital Hardware Cost by reducing the required number of RF chains at TX and RX sides
- Provides Energy Efficiency by potentially reduces the downlink and uplink transmit power through coherent combining and an increased antenna aperture
- Reduces Operational Cost when employing large array of antennas by allowing the use of low-cost RF amplifiers in the milliWatt range,

***Challenges***

- Constant magnitude constraint enforced by analog phase shifters
- Finite quantization of analog phase-shifters results in programming problems
- Limited CSI availability leads to difficulty in UL and DL channel estimation
- Limited to narrowband operation

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[1] Ning, B., Tian, Z., Chen, Z., Han, C., Yuan, J., & Li, S. (2021). Prospective beamforming technologies for ultra-massive MIMO in terahertz communications: A tutorial. *arXiv preprint arXiv:2107.03032*.

# Wideband Beamforming

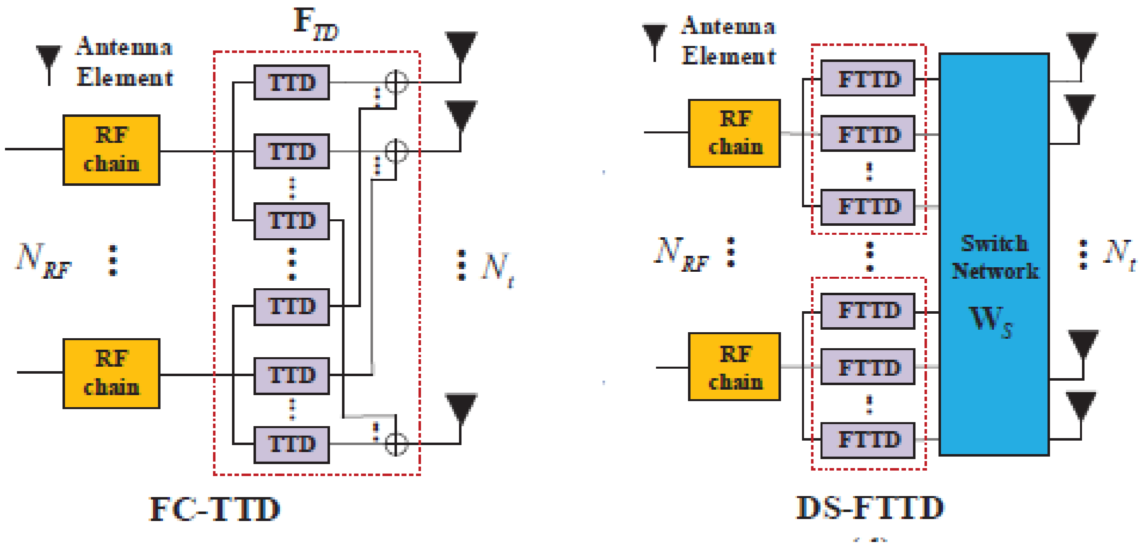


*Fig: Fully-connected vs Dynamic sub-array TTD architectures*[1]

**Spatial wideband effect**
- Signal envelope received by different antenna elements might not belong to the same symbol
- Phased array cannot effectively combine the signals
- Dividing the baseband into several sub-bands and concurrently processing each sub-band that has a lower symbol rate by the digital beamformer.

- TTD architecture addresses both spatial wideband and frequency-wideband effects
- Compensates for the effects of space and frequency by imposing a true time delay on the signal at each antenna element
- Suffers from high hardware complexity and cost in analog domain as there are many RF chains and the dynamic range requirement is extremely high
- Easily be realized in the digital domain

**Frequency wideband effect**
- Signal components of different frequencies arrive at the array with different phase differences
- Same phase compensation cannot simultaneously maximize the beam gains at all frequencies
- Beam pattern changes with the frequency of the signal (beam squint effect)

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[1] Ning, B., Tian, Z., Chen, Z., Han, C., Yuan, J., & Li, S. (2021). Prospective beamforming technologies for ultra-massive MIMO in terahertz communications: A tutorial. *arXiv preprint arXiv:2107.03032*.

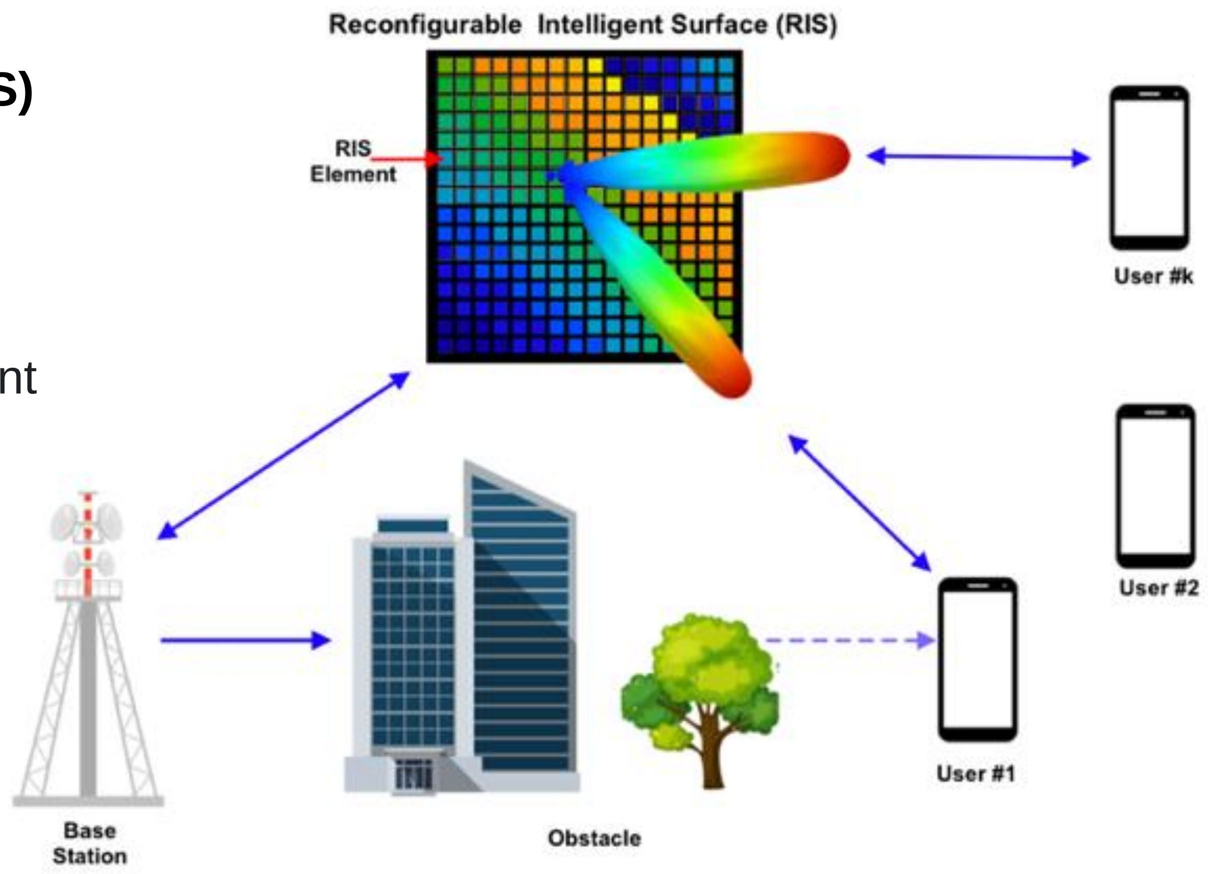
# Reconfigurable Intelligent Surfaces – Assisted Joint Beamforming



Small wavelengths at 5G/6G mm-Wave frequencies are subject to path losses and multipath scattering leading to beam blockage

**Reconfigurable Intelligent Surfaces (RIS)** supersede relay performance using large apertures with simple circuitry.

- ✓ Spectrally more efficient
- ✓ RIS reduce hardware complexity.

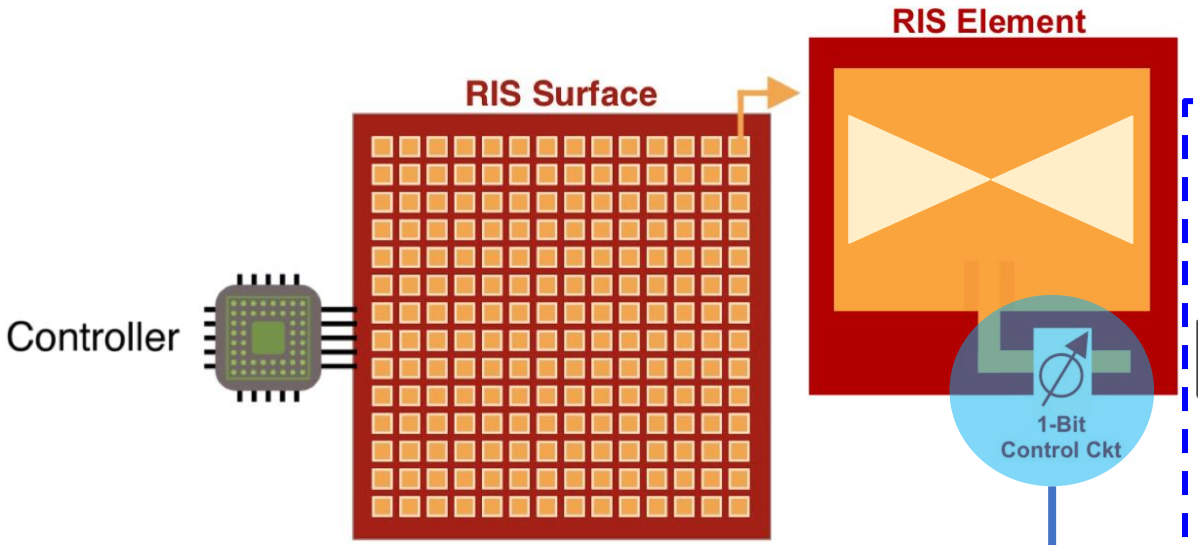



**Alternative Technology: Relays**

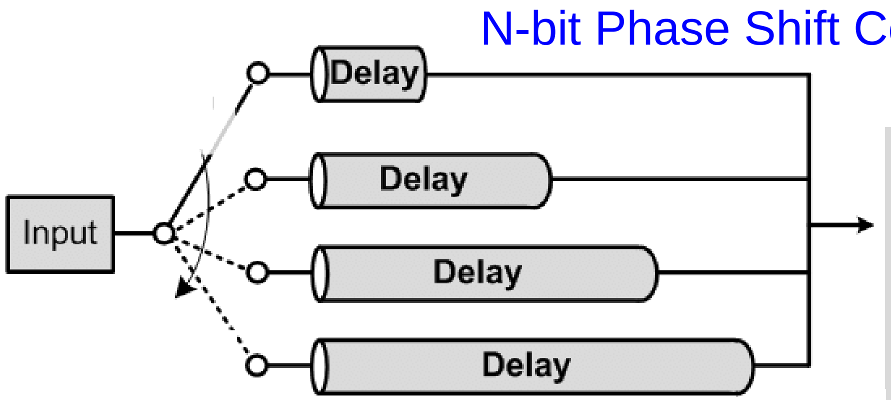
- × A dedicated power source per relay
- × Reception and re-transmission circuitry
- × Signal processing complexities.

**Goal:** Beamforming and adaptive nulling using RIS via a very simple circuitry (in terms of SWAP-C)

# RIS Beamforming with 1-bit Phase Shifters




A **control circuit** required to provide beamforming excitation in each RIS element




- For an n-bit phase control, every element requires n control lines per RIS element.


**RIS Challenge:**

- RIS requires large apertures for high-gain arrays.
- Bulky/complex beamforming networks that hinder surface integration and deployment.

1-bit phase shifters for RIS elements

- ✓ Hardware electronics, significantly reduced
- ✓ Reduction in optimization complexity
- ✓ Beamforming circuitry easier to package, deploy and integrate.



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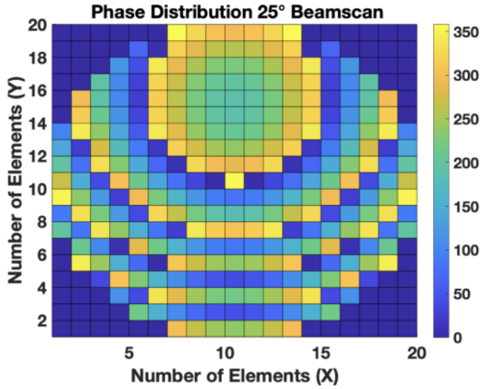
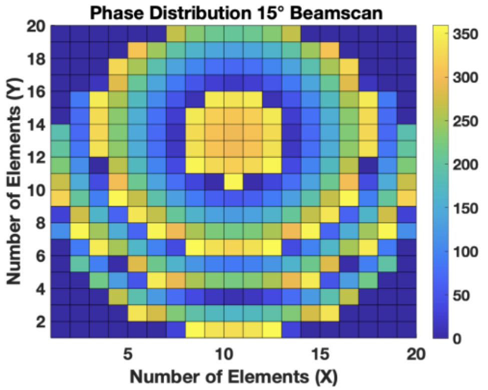
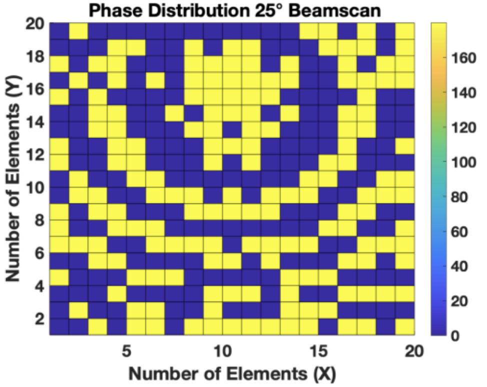
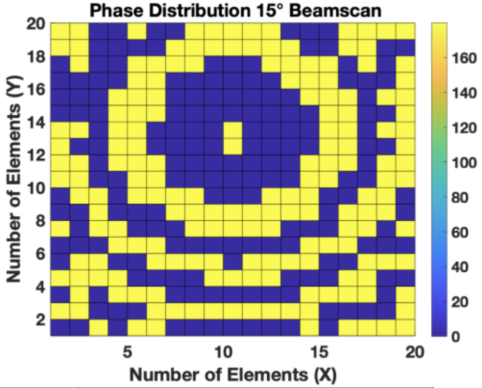
# Comparison Between 1-bit vs. 6-bit Phase Distributions

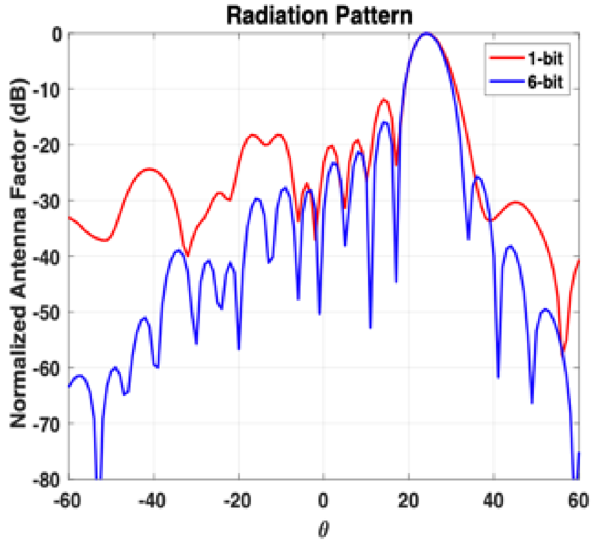


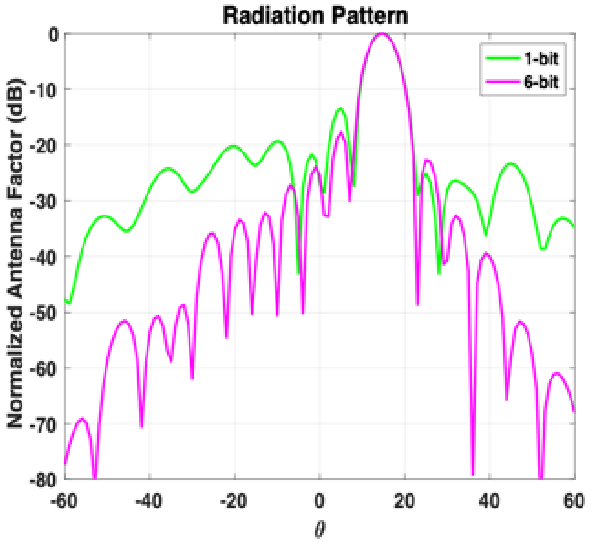



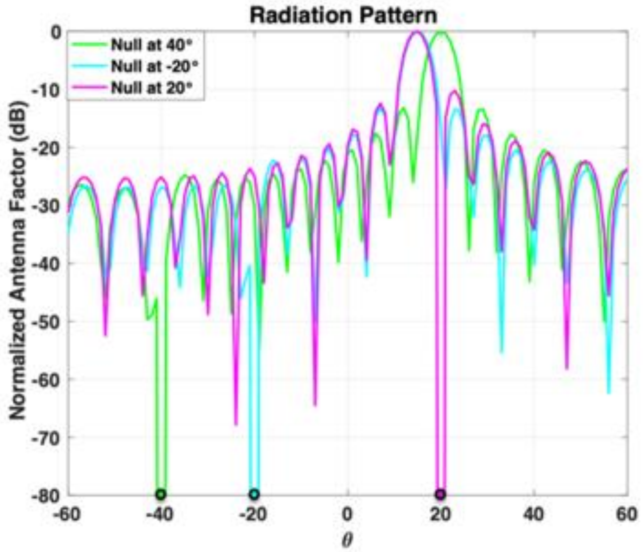




| Direction | Directivity 6-bit | Directivity 1-bit |
|---|---|---|
| 25° | 20dB | 16dB |
| 15° | 23dB | 19dB |




- **2400 digital control lines** required using a 6-bit network.
- **Only 400** digital control lines are needed for a single bit configuration.

**→6-fold reduction in DC power.**

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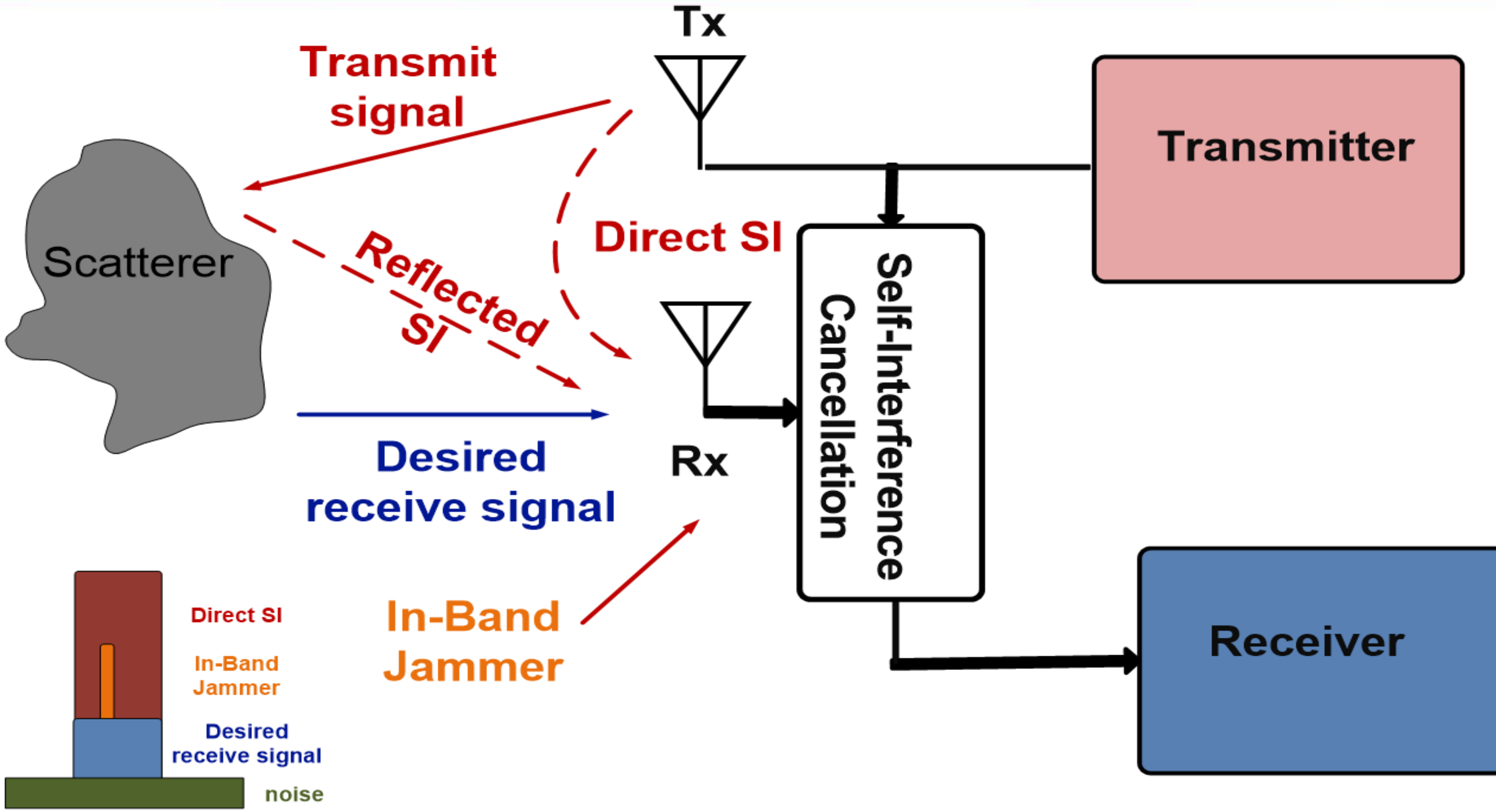
IMAPS 19th Conference on DEVICE PACKAGING | March 13-16, 2023 | Fountain Hills, AZ USA

# Interference mitigation techniques for next-generation radios

RF systems are prone to:
1) In-band External Jammers
2) High Power self-interference in simultaneous transmit and receive systems.




Direct self interference and in-band jammers cause receiver desensitization

More efficient use of the available spectrum requires:
1- Self-Interference cancellation through Simultaneous Transmit and Receive (STAR) to double spectral efficiency
2- Interference/Jamming mitigation (~40 dB) through channel coding and modulation

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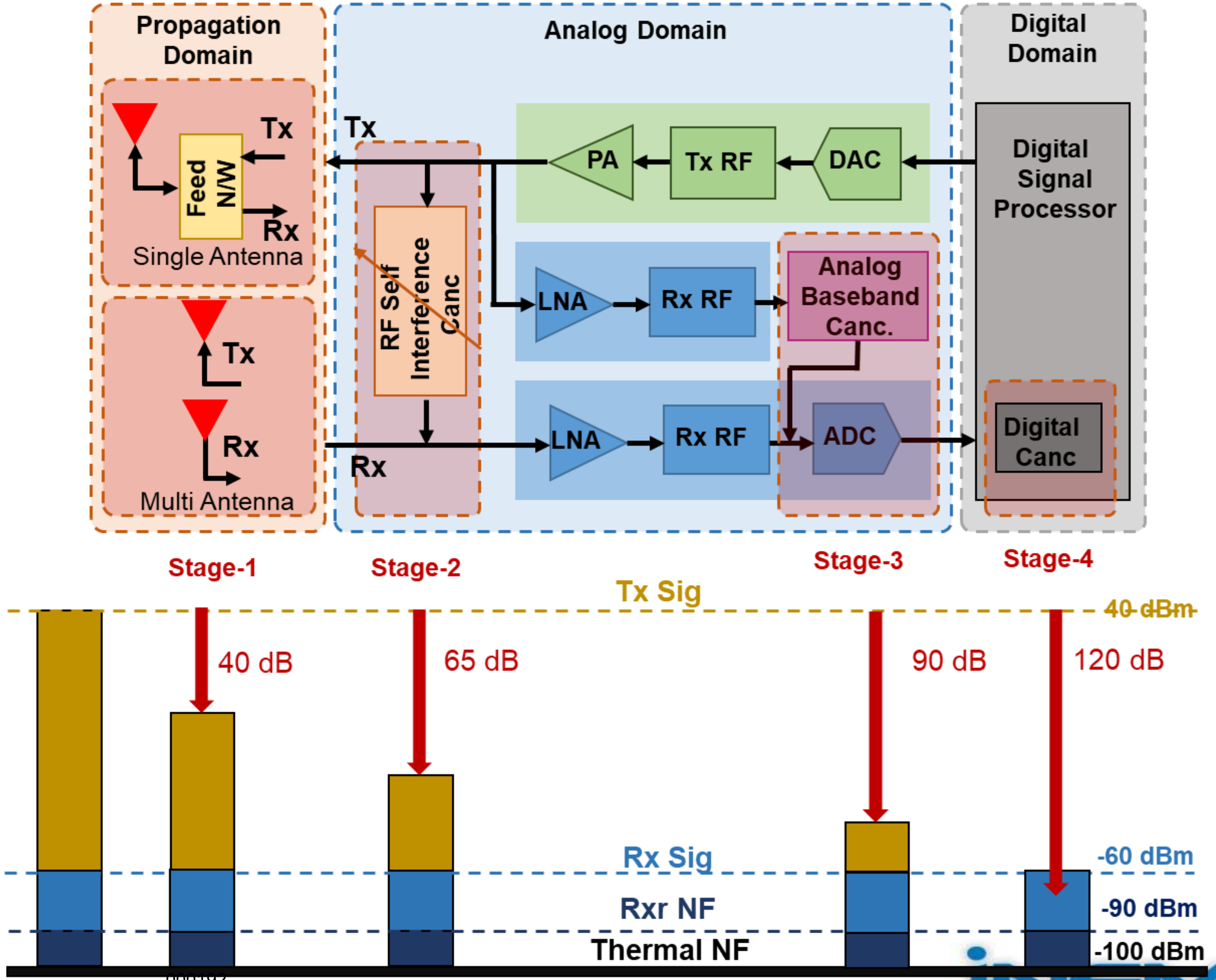
# R2: Advanced Techniques To Address Spectrum Coexistence And Improve Spectral Efficiency

**Different STAR architectures considered to account for Tx coupling on to Rx chain:**

- All components should be suppressed as much as possible
- > 50 dB suppression of main signal required in this case
- > 30 dB suppression of non-linear components, including harmonics and Tx noise
- Tx signal, Tx nonlinearities (harmonics + noise) are to be suppressed equally

With proper Self-Interference cancellation, STAR achieves **twice the capacity** as compared to TDD/FDD.



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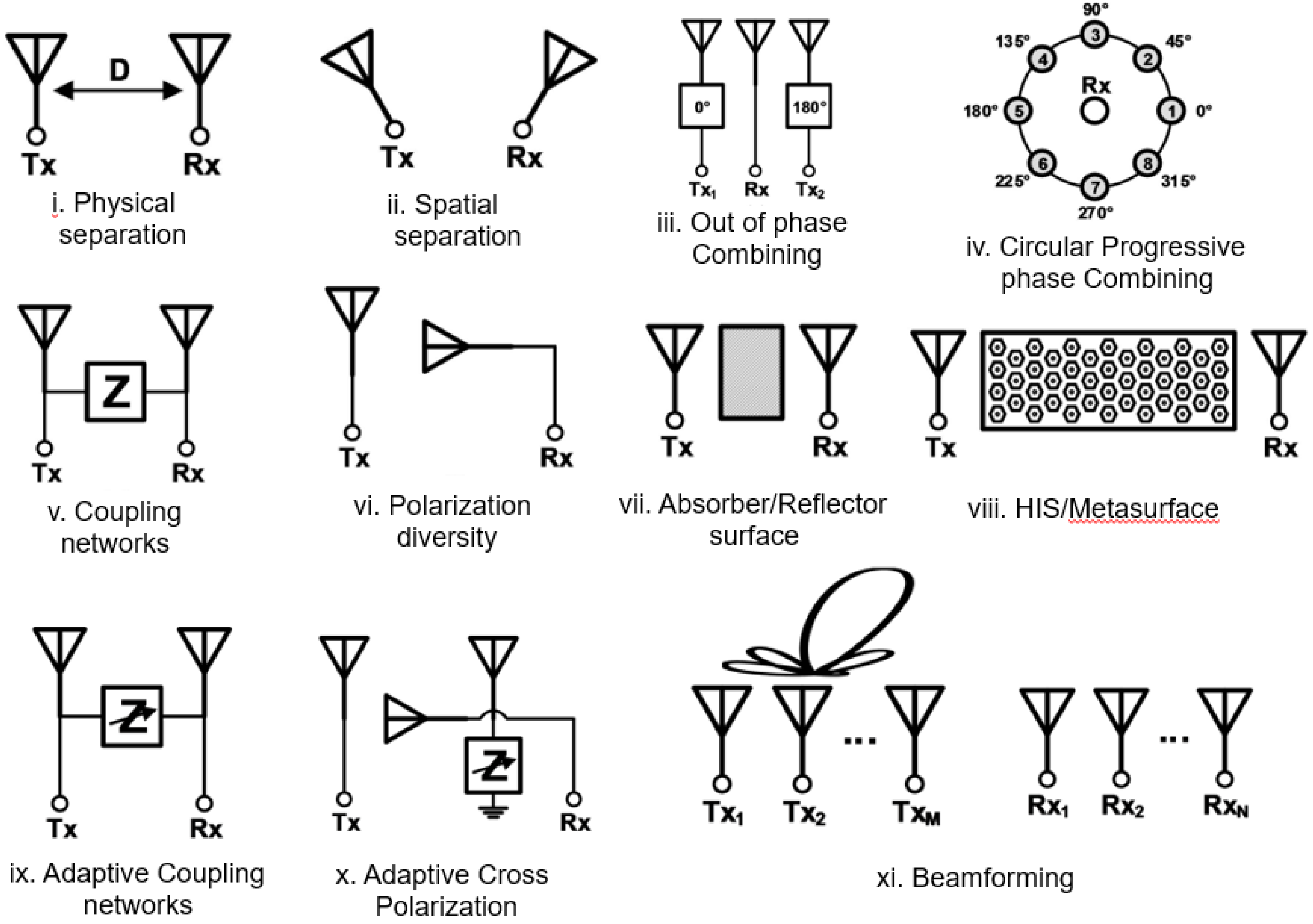
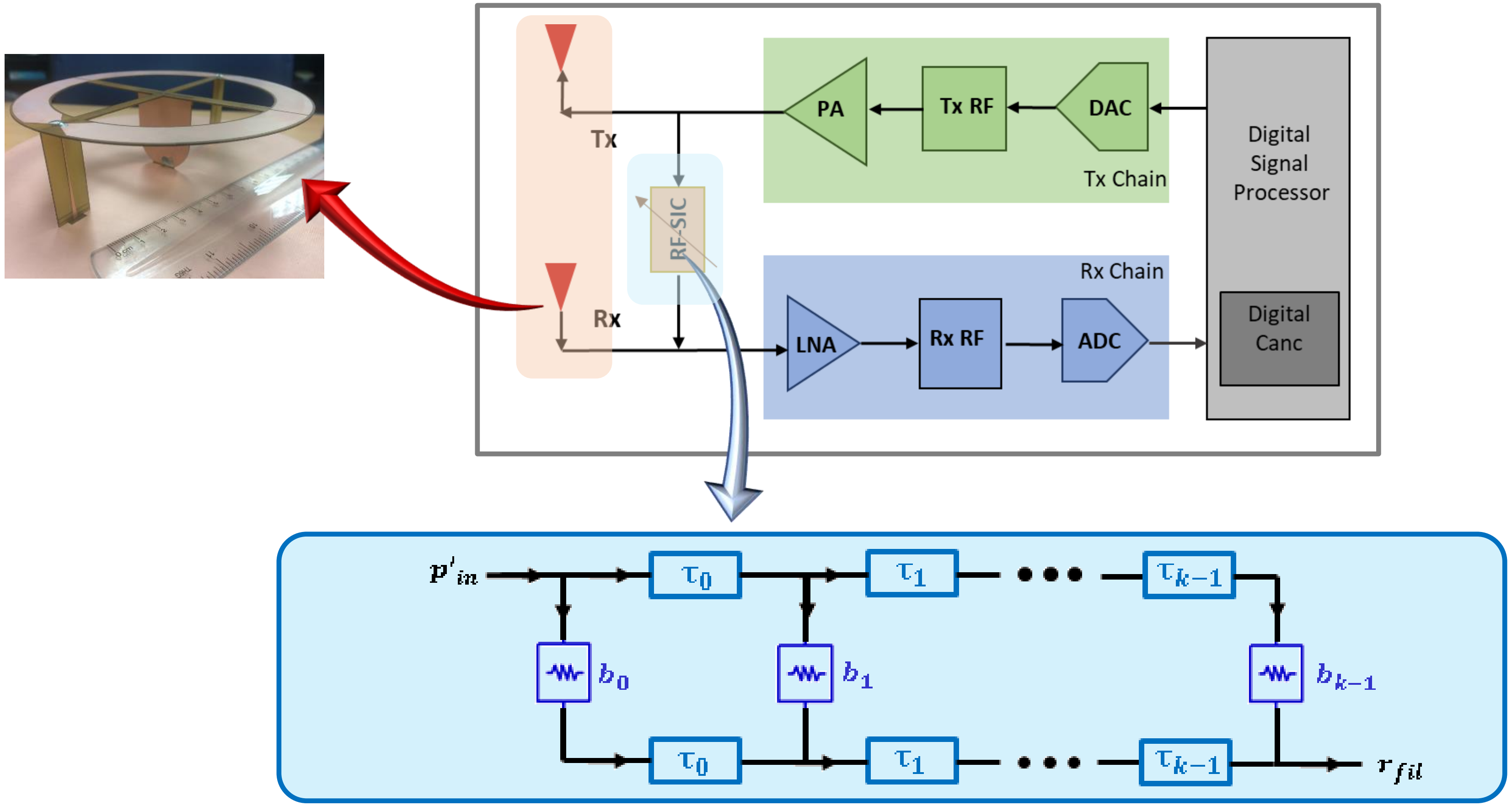
# Stage-1: Different Cancellation Techniques in a Multi-antenna System




[4] K. E. Kolodziej, B. T. Perry, and J. S. Herd, "In-band full-duplex technology: Techniques and systems survey," IEEE Transactions on Microwave Theory and Techniques, vol. 67, pp. 3025-3041, 2019.

# Stage-2: Design of Multitap RF-SIC Filter to Match Antenna Response

## RF-SIC Filter Design




- Estimate proper filter order
- Optimize variable and realize as transmission lines the optimized W and L values
- Attenuators are also optimized accordingly

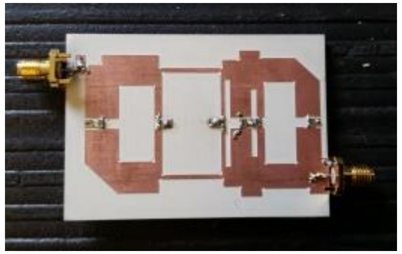
# Measured RF Filter Response of Mutlitap FIR Filter Prototypes

**Accomplished**

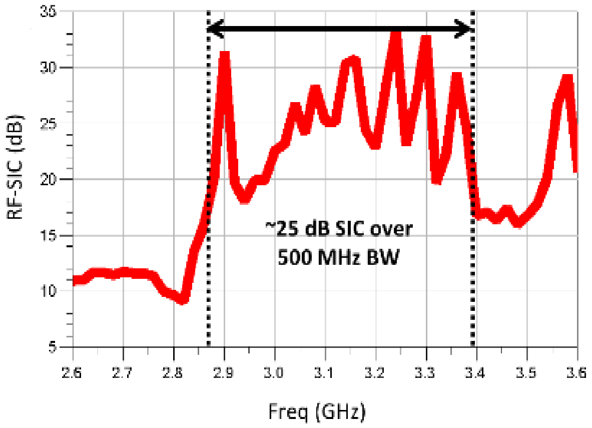
1) **Fabricated and tested prototype 1**
   - Instantaneous operational bandwidth of 500 MHz
   - 6 filter taps with variable microstrip L and W used
   - Measured RF cancellation of ~25dB over 500 MHz

2) **Fabrication of 1GHz RF filter with:**
   - Employed filter banks to realize wideband operation
   - Reduced foot print
   - 12 taps to operate over 1 GHz

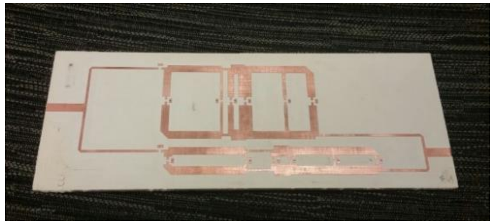
**1st Prototype – 0.5 GHz**



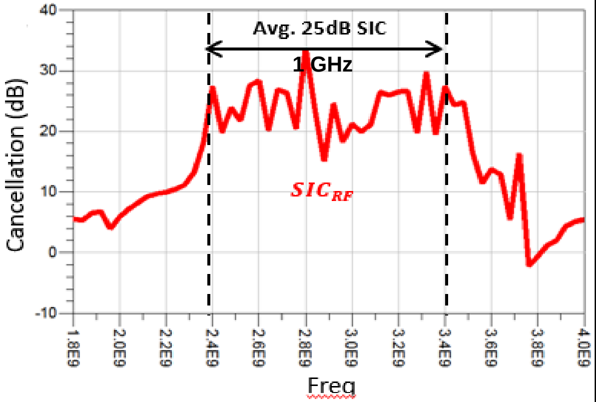
**Measured RF Cancellation**




**2nd Prototype – 1 GHz**

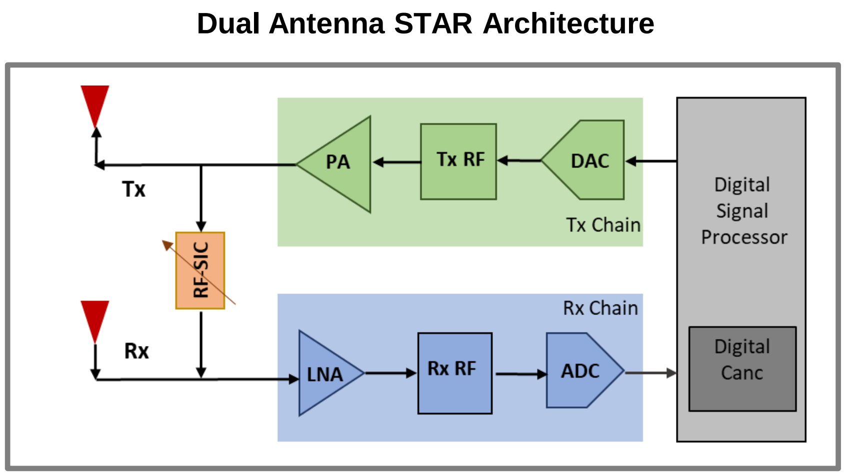


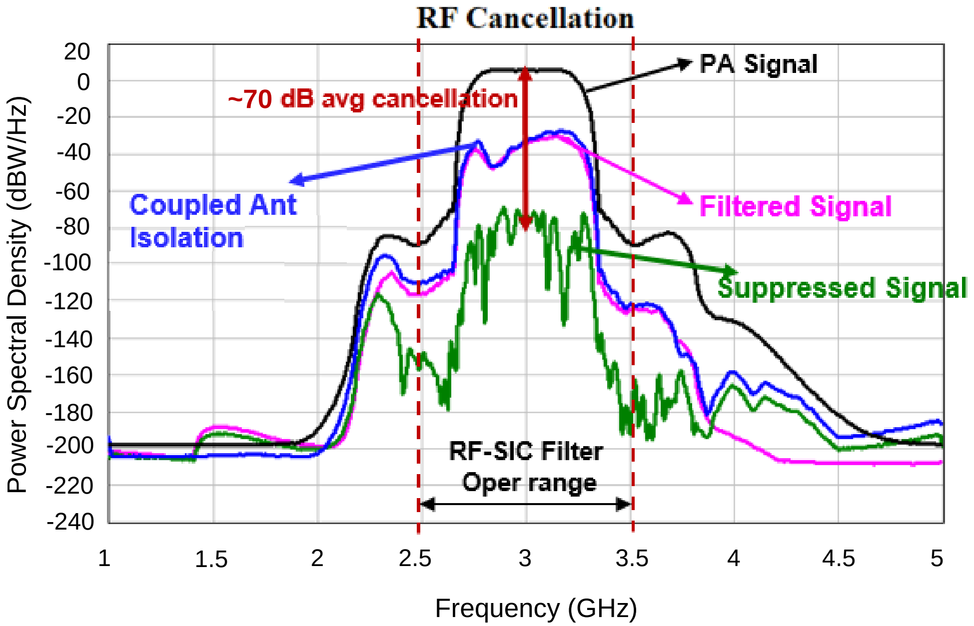
**Measured RF Cancellation**




For the first time, we demonstrate RF cancellation of ~25 dB over 0.5 and 1 GHz

# Combined 2-stage cancellation of STAR transceiver Over 1 GHz bandwidth




**1) Design of 1GHz RF cancellation filter with:**

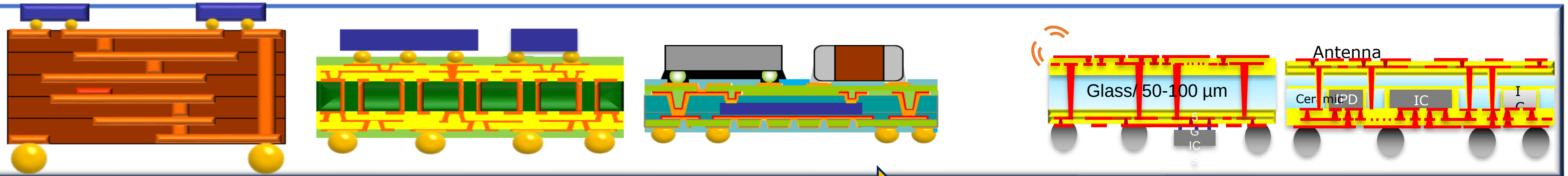
- Filter banks using 12 taps
- Conformal design
- Achieved cancellation of ~25dB over 1GHz

**2) Modified STAR architecture to account for Tx noise influence of the cancellation:**

- Tx noise cancelled by sourcing a part of it directly to RF filter
- RF filter designed to include mutual coupling effect from nearby elements

# RF Module Evolution

| Bands | WLAN GHz | LTE Carrier Aggregation | 5G by GT Sub-7 GHz | mm wave 28-44 GHz and beyond |
|---|---|---|---|---|




| | | | |
|---|---|---|---|
| Substrate | LTCC Thick laminate | 7-10 layer laminate Coreless substrate | 4-6 ML on Panel Glass with TPV |
| Passives | Discrete LTCC | Laminate-embedded passives SAW/BAW CSPs | mm wave Distributed filters |
| Shielding | Metal Lid | On-Mold | Component-Level Shield |
| Chip Assembly | Wirebond | Flipchip | GPE and doubleside comp With thin Cu nanopads |
| Board assembly | LGA | LGA or BGA (backside assembly) | |

# Substrates and Design Rules

- High-density, impedance-matched (2-5%) and low-loss transmission lines:
  - High-density RF and digital in the same package
  - Smooth surface for low losses:
- Create thinfilm components:
  - Decoupling for high-speed mm wave lines
  - Tunable and reconfigurable components
- Seamless layer-to-layer and 3D interconnects
  - Impedance-matched TPVs
  - Minimal signal discontinuities and reflections with ultra-fine vias and pads
  - Better termination of E-fields with multiple ground vias or arrays – Lower noise coupling with less mutual and self-inductance
  - Minimal ground bounce and resonance effects with small clearances (less intrusion) in power planes
- Precision circuitry for impedance matching
- Package- and board-level reliability
- Availability in 30-100 microns
- Large-area panel processing

| | **LTCC** | **Laminates** | **Glass** |
|---|---|---|---|
| **Substrate thickness** | >500 mm | >300 mm | <150 mm |
| **Feature size with 5% precision** | 100 mm | 40-50 mm | 10-20 mm |
| **Through-via diameter and pitch** | 100mm/ 300mm | 100 mm / 300 mm | 25 mm/ 50 mm |
| **Through-thickness variation** | >25 mm | >10 mm | 0.5 -1 mm |
| **Manufacturing Panel size (metric for cost)** | 150-200 mm | 510 mm | 510 mm |

# Materials: LTCC to Laminates, FOWLP and Glass

- Glass is a promising candidate for next-generation substrate material for 5G applications

| | Flip-Chip | | | Chip-Embedding | Flip-chip & Embedding |
|---|---|---|---|---|---|
| Characteristic | PCB-based | LTCC | Organic laminates | FO-WLP | Glass |
| **Material Properties** | | | | | |
| Relative dielectric constant (εr) | 4 | 5 – 10 | 2.9-3.2 | 3.68 | 2.7 – 7 |
| Loss tangent × $10^4$ (tanδ @ GHz) | 20 @ 10 | 12 @ 10 | 40 @ 60 | 80 @ 58 | 3 – 50 @ 10 |
| Surface roughness (nm) | 300-5800 | 177 | 400-600 | > 1000 on EMC | <1 |
| Coefficient of thermal expansion - CTE (ppm/K) | 17 | 5.5 – 7.2 | 17 | 30 (EMC) | 3-8.5 |
| Dimensional stability - Young's Modulus (GPa) | 21 – 24 | 90-150 | 10-40 | 22 | 50-90 |
| Water absorption | 0.1%-0.25% | 0 | 0.040 % | | 0 |
| **Process Challenges** | | | | | |
| Multi-layer process alignment | | | | | |
| Small-feature patterning | | | | | |
| Thin substrate reliability | Warpage | | Warpage | | Cracking |



*Atom Watanabe et al., (Georgia Tech PRC)*

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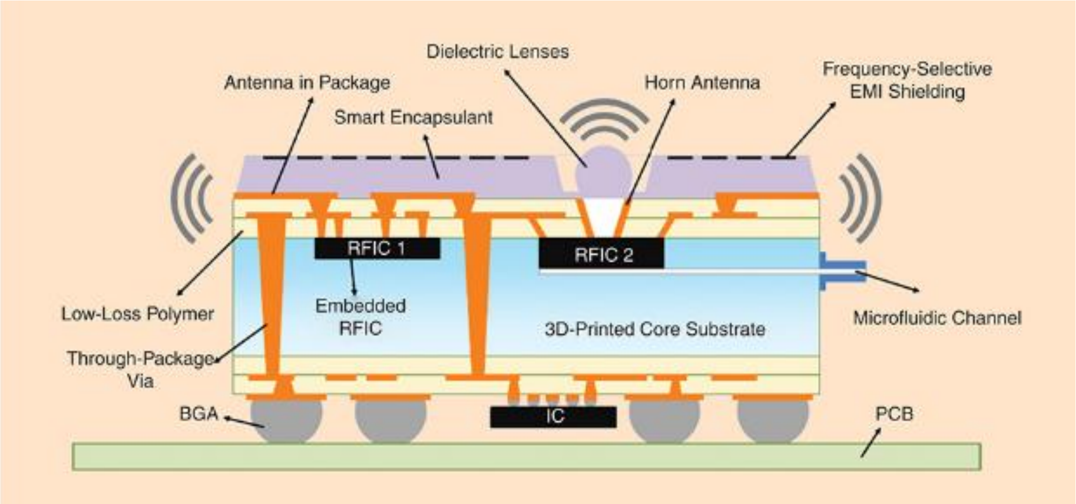
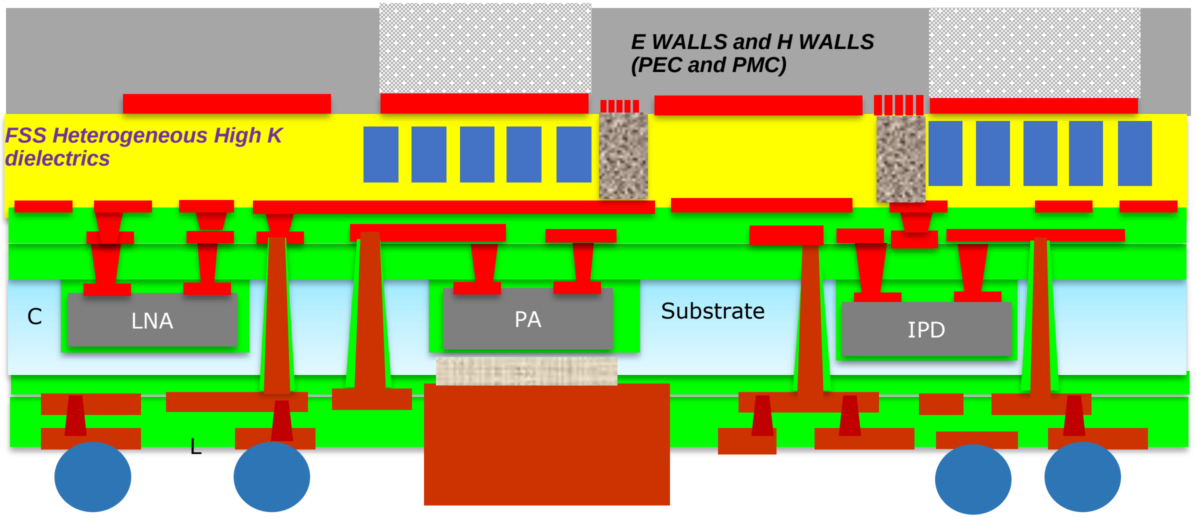
# 5G/mmWave Package Integration



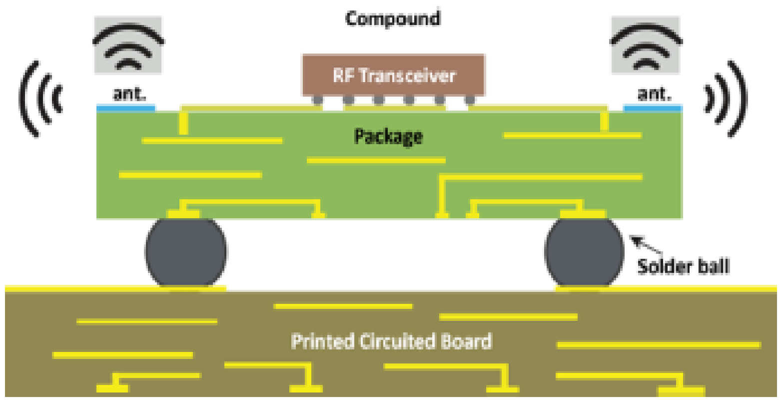

- High-density and low-loss transmission lines:
- Ultra-fine vias and TPVs for seamless 3D interconnects
- Precision circuitry for impedance matching
- Smooth surface for low losses

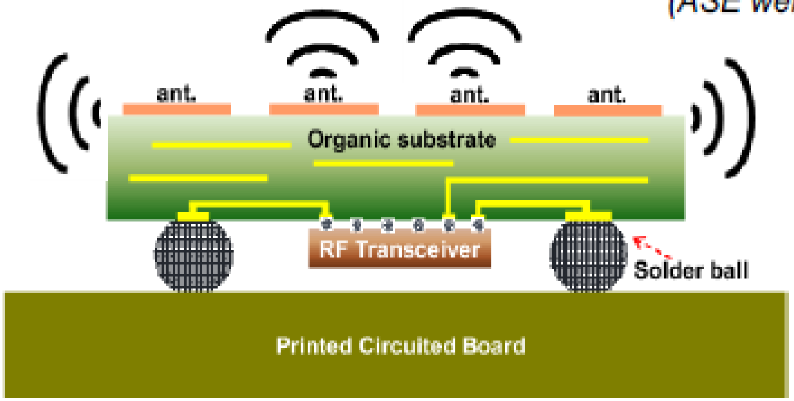
- RF and digital in the same package
- Advanced antenna array for wideband and gain
- Embedded FSS for improved performance
  - Heterogeneous high-K superstrates as lenses,
  - E walls, H walls, AMCs
- Package- and board-level reliability
- Large-area panel processing

# Antenna-in-Package (AiP)

## Flip-chip AiP (FC-AiP)

**5G mm-Wave package for Apple's iPhone 12 from ASE**




*(ASE website)*

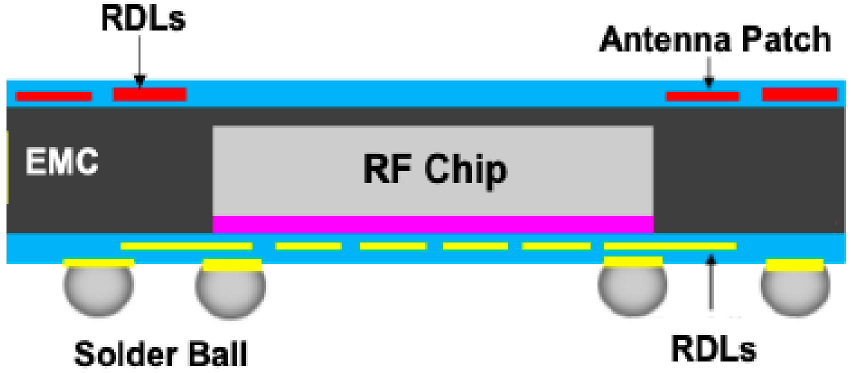
(+) Low cost, Mature process

(-) Form-factor, Package parasitics

## Fanout AiP (FO-AiP)

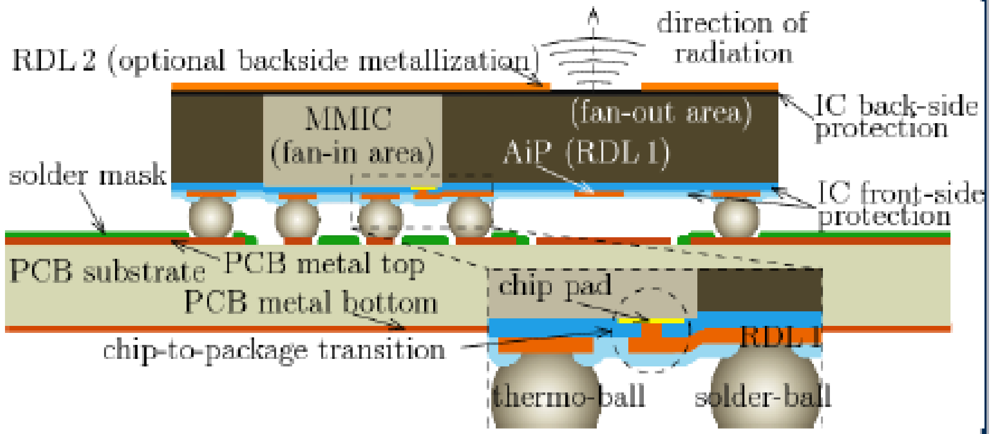
**TSMC InFO-AiP for 5G mm-wave**

*(TSCM, ECTC'18)*




**Infineon eWLB for radar**

*(Infineon EWLB, EUMC '18)*




(+) Lower cost

(+) Form factor

(+) Performance (no bump parasitics)

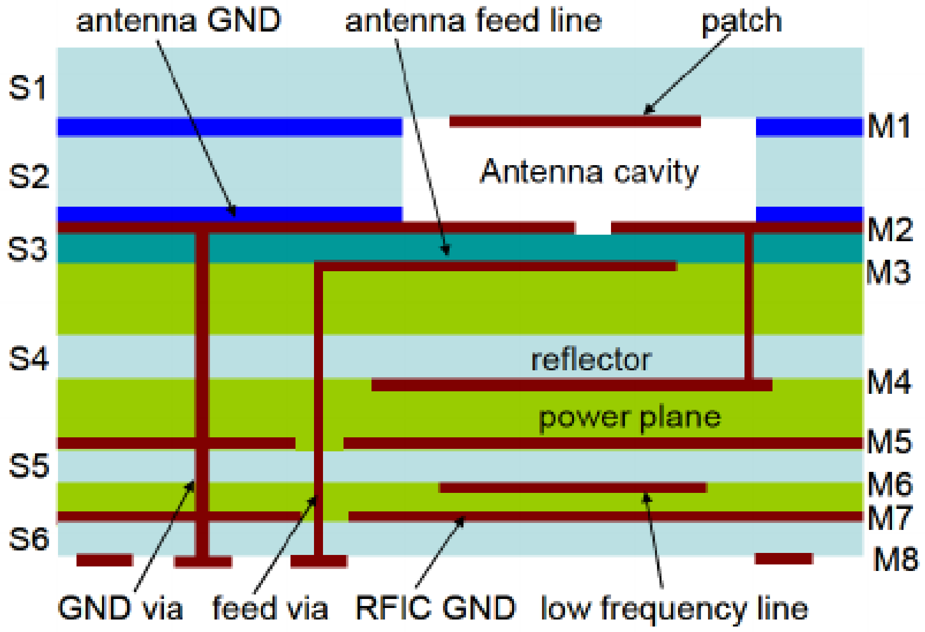
# Antennas: Planar, Stacked and Broadband

For resonator antennas, bandwidth enhancement with:

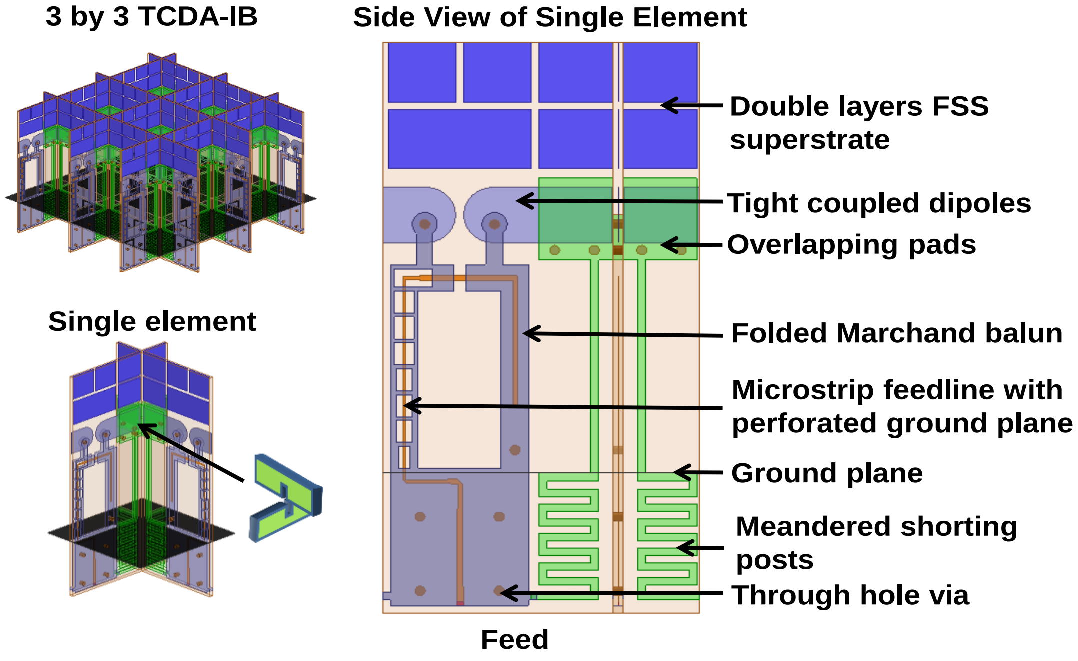
- Irregular shapes
- Stacked antennas with different materials
- Air cavity: mitigates surface waves and increases bandwidth
- Fractal antennas, where the golden ratio is maintained
- Defected ground structures where a rectangular defect is etched at the center of the ground plane
- Via-array for isolation

For aperture antennas:

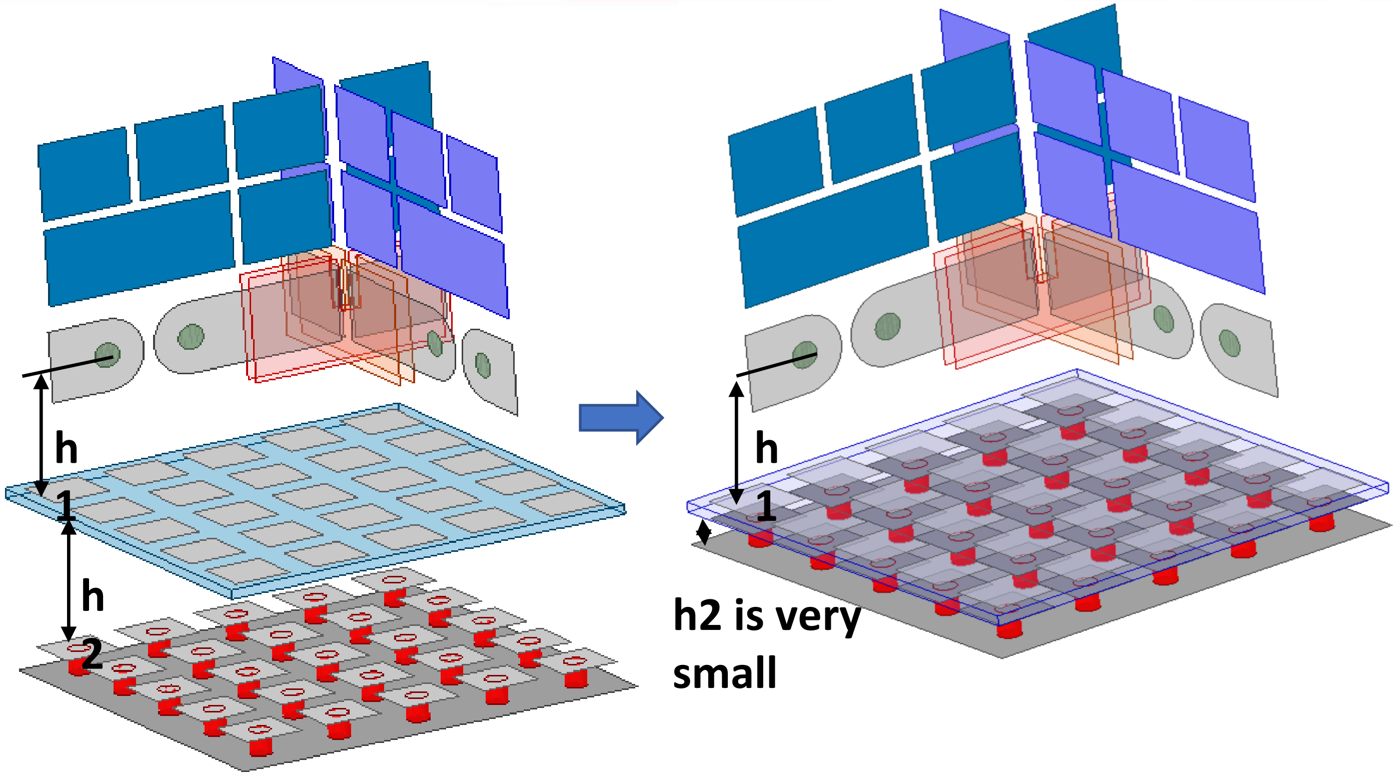
- Enhanced inter-element capacitive coupling to increase the bandwidth
- Integration of Marchand Balun to further expand bandwidth.
- RSS (resistive substrate card loading) for increasing the bandwidth,
- Introduction of FSS superstrates




IBM, Sadhu et al..



# Ground Height Reduction with Printed Resistive FSS




- As HIS operating bandwidth have some limitation, TCDA ground height reduction is limited upto the semi-resistive FSS.
- TCDA ground height can be reduced significantly as the phase of the reflected wave can be controlled using HIS ground planes.

- Implement reflector type high impedance ground plane to minimize phase cancellation.
- Implement high impedance surface as ground plane to kill the surface wave which causes back radiation.
- Using the HIS ground plane the ground height can be reduced.



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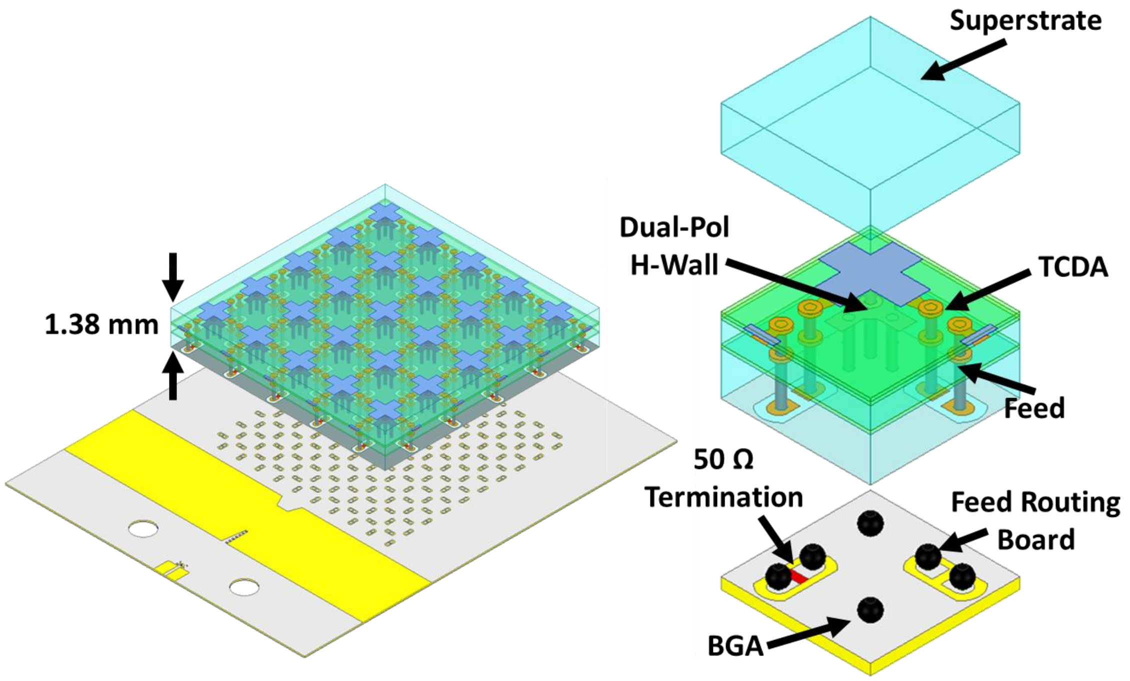
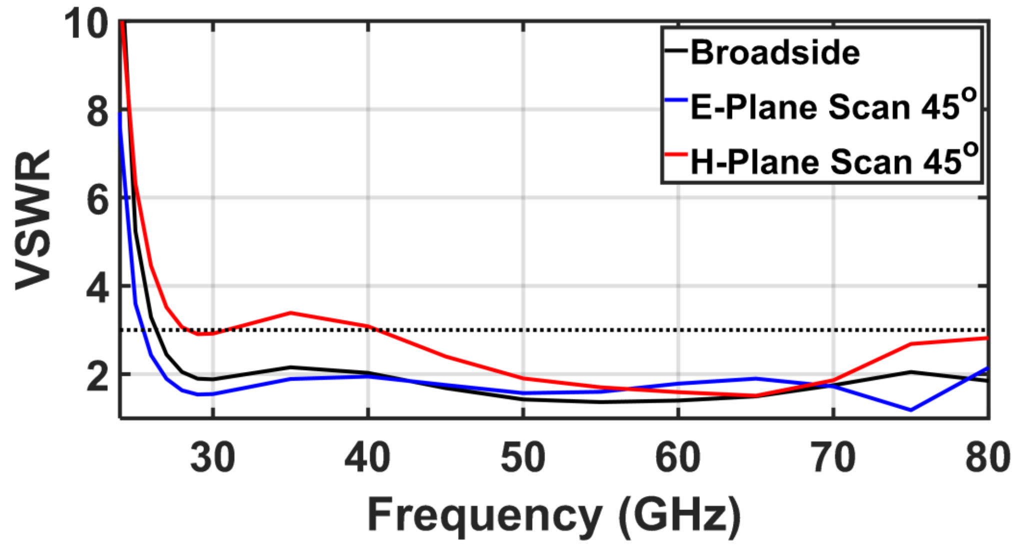
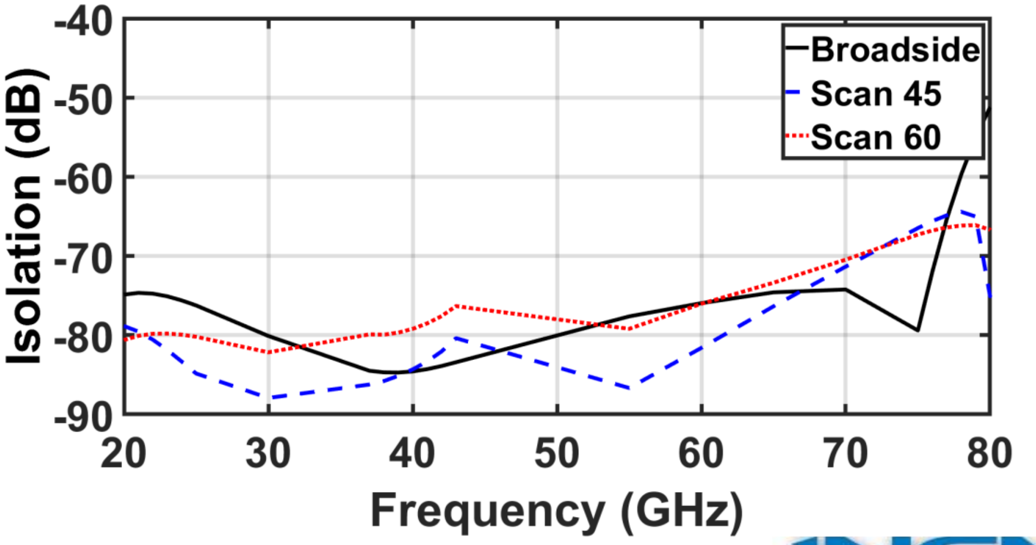
# High Isolation mmWave Antenna for 5G and ISM




**This prototype has:**

- A wideband feed
- Dual linear polarization
- VSWR < 3 for 22 GHz to 80 GHz
- Resonance free scanning to 45˚
- $H_{Total}$ = 1.38mm

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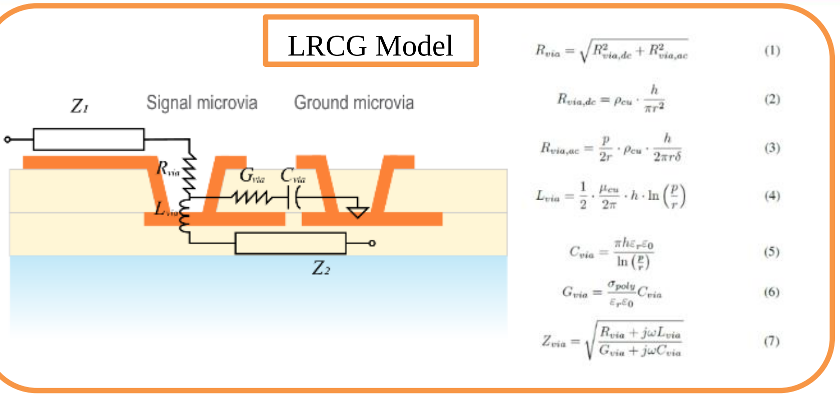
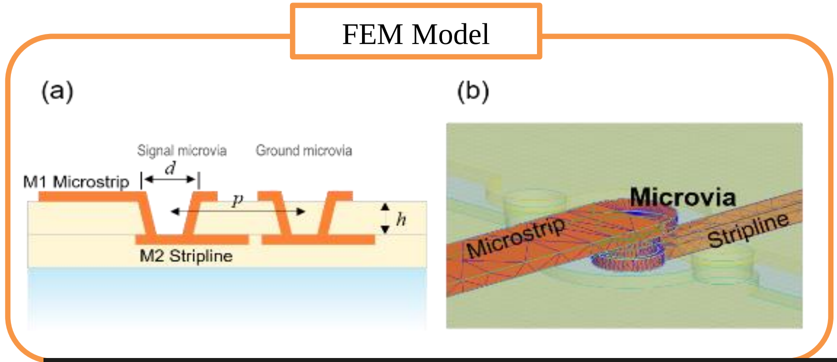
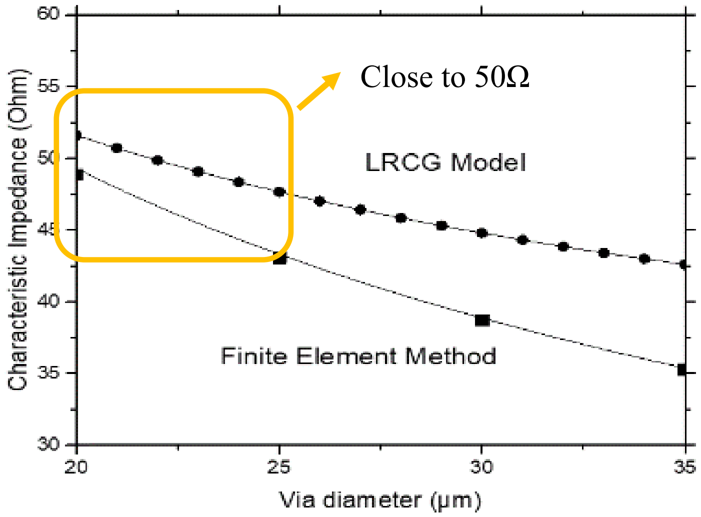
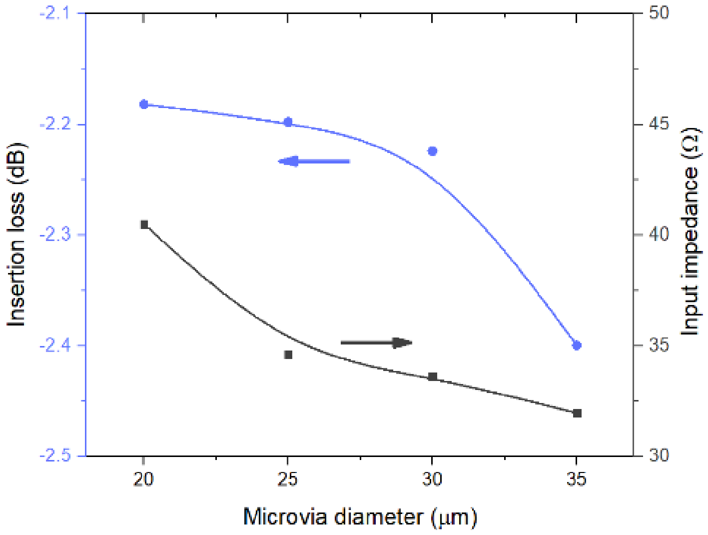
# Interconnects: Fine-Vias for Impedance Matching



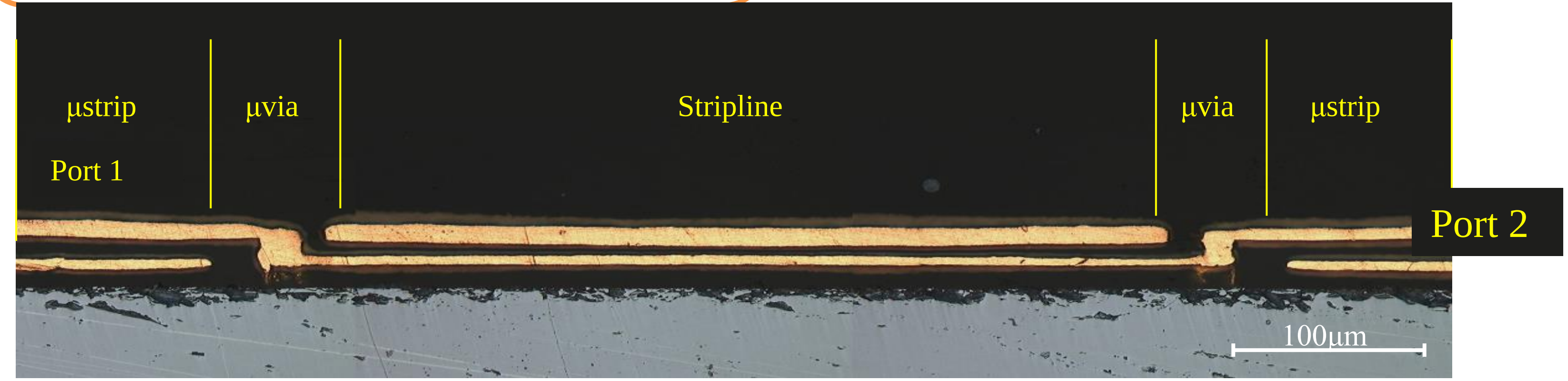



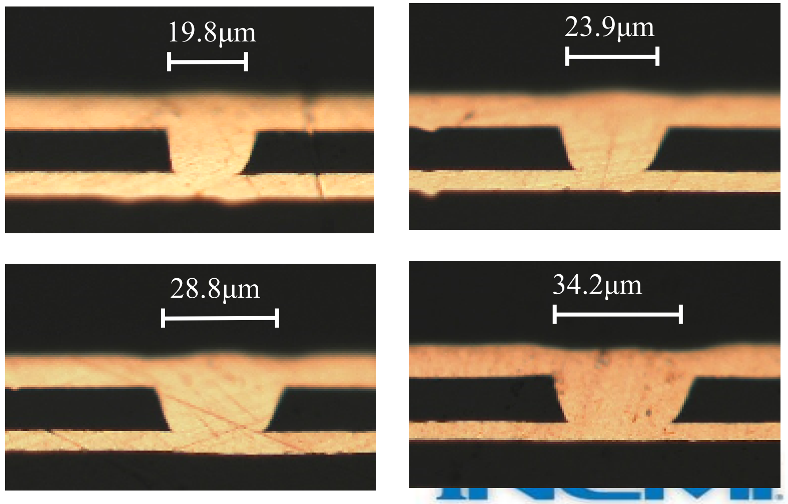




| $r_{via}$ | $Z_{via}$ | $20\log(S_{11})$ | VSWR | $20\log(S_{21})$ |
|---|---|---|---|---|
| ↓ | ↑ | ↓ (Less reflection) | ↓ (Closer to 1) | ↓ (Lower loss) |

*(Slide from Atom Watanabe, GT-PRC*




- ❑ Daisy-chain test vehicle with precise microvia-diameter control to measure microvia losses

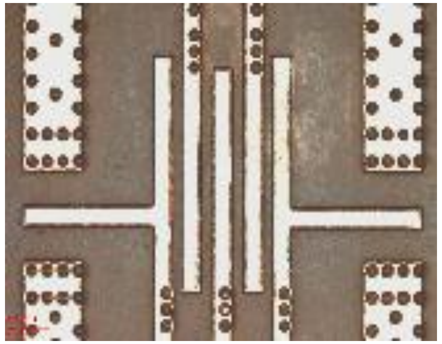
# High-Performance 5G and LTE Passive Devices

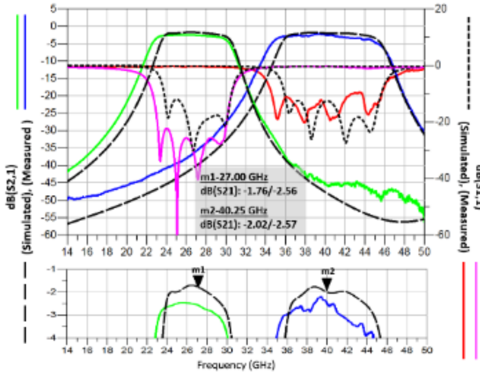
## 5G Filters in 50-100 micron glass- or ceramic-core laminates (Muhammad Ali et al., GT-PRC)

- Ultrathin filters: 2X thickness in reduction compared to offchip filters;
- Lower insertion loss compared to on-chip filters

**High Q Inductors and LTE Diplexers in glass and glass-core laminates**

| | | | | |
|---|---|---|---|---|
| On-Chip | 4 dB | 0.1 dB/mm | Very Small ($<4\lambda_0^2$) | Very Small (<500µm) |
| Traditional Off-Chip | 2 dB | 0.5 dB/mm | Small-Med. ($\sim4\lambda_0^2$) | Med.-Large (˜500µm) |
| On-Package – 3D Module | 2.5 dB | 0.2 dB/mm | Very Small ($<4\lambda_0^2$) | Small (<500µm) |

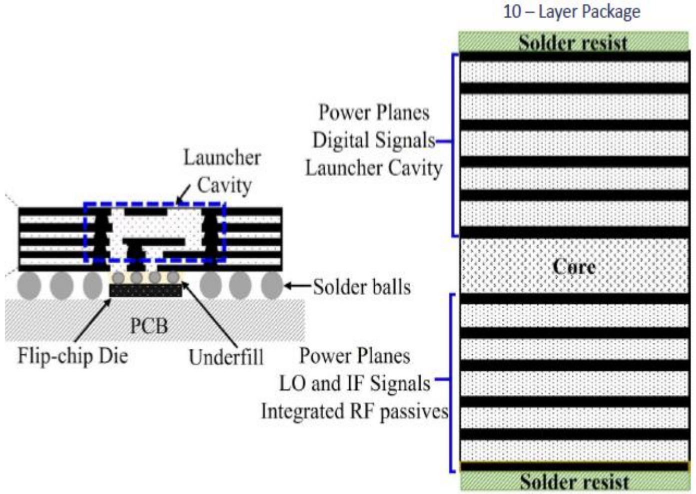





- Ultra-fine mm-wave structures with high precision
- Footprint smaller than 0.5
- Innovative topologies for low insertion loss

## Filters in the 100-330 GHz bands (from Neelam Gaunkar et al., Intel)

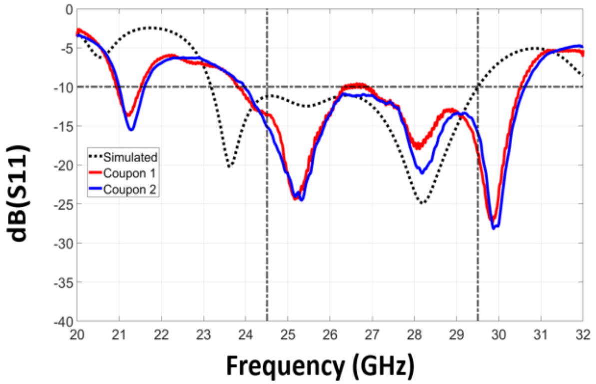
| Parameter | | | | |
|---|---|---|---|---|
| w | 10 | 3.2 | 2 | 3 |
| IL (dB | 4-5 | 3-5 | 1.7 | 5-7 |
| Size (mm x mm) | 1.9 x 1.35 | 2 x 0.26 | 20 x 20 x 40 | 0.7 – 1.1 |
| Type | Microstrip | Stripline | RWG | SIG |
| Substrate | Organic | Silicon BCB | Metal | Organic |
| Operation band | 100-140 | 125-152 | 200-225 | 225-330 |

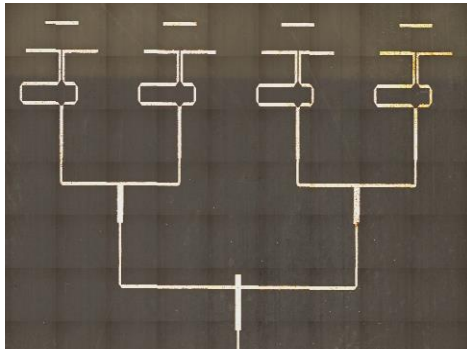


# Power Dividers and Antenna Arrays in Package

**Power-dividing networks and High-Gain Antenna Arrays**

| Power Divider and Yagi-Uda Antenna Array | Added Insertion Loss | Realized Gain (27 GHz) | Antenna Array Efficiency |
|---|---|---|---|
| Two-Way, 2×1 | 0.4 dB | 6.96 dBi | 80% |
| Three-Way, 3×1 | 0.6 dB | 8.24 dBi | 85% |
| Four-Way, 4×1 | 0.86 dB | 9.51 dBi | 82% |

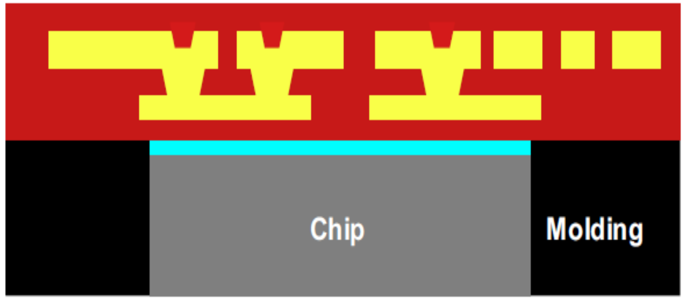


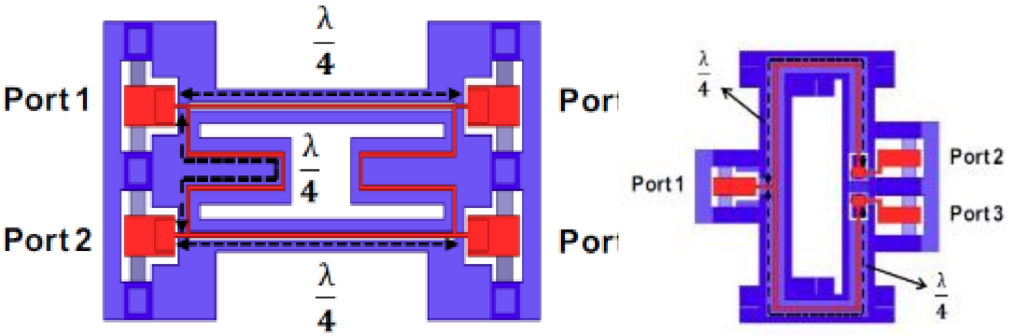



*With Atom Watanabe, Muhammad Ali, Tong-Hong Lin, Manos Tentzeris, Rao Tummala et al., (Georgia Tech PRC)*

**Power-dividing networks and High-Gain Antenna Arrays**

**InFO (EMC)**




Transmission line insertion loss 0.34 dB/mm
Passive element insertion loss 4.3 – 4.9 dB

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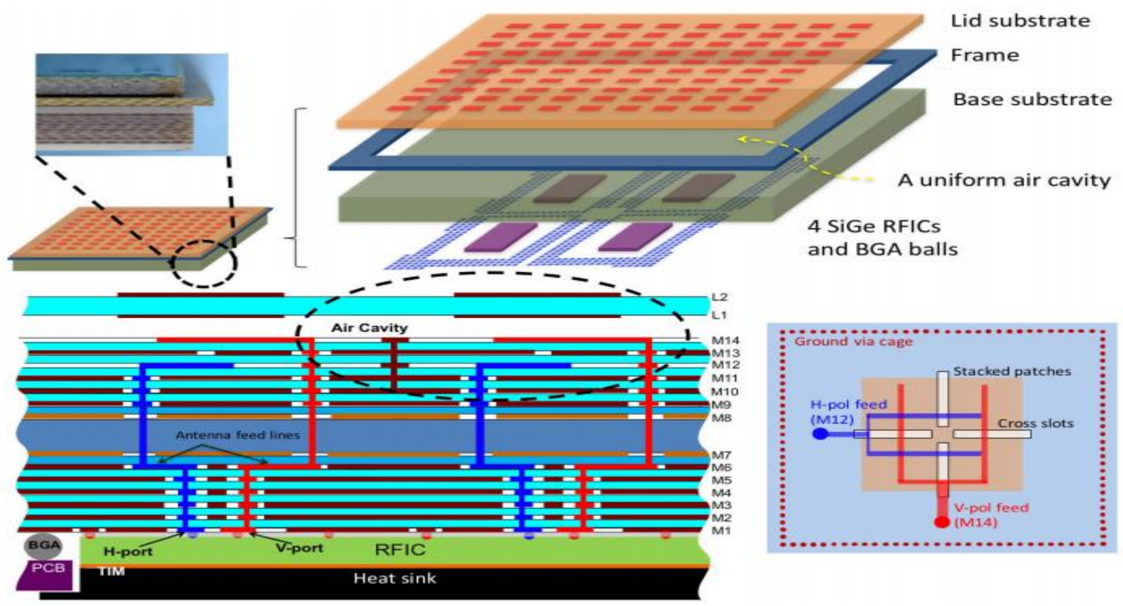
K. F. Chang *et al*., "77-GHz Automotive Radar Sensor System With Antenna Integrated Package," in *IEEE Transactions on Components, Packaging and Manufacturing Technology*, vol. 4, no. 2, pp. 352-359, Feb. 2014.

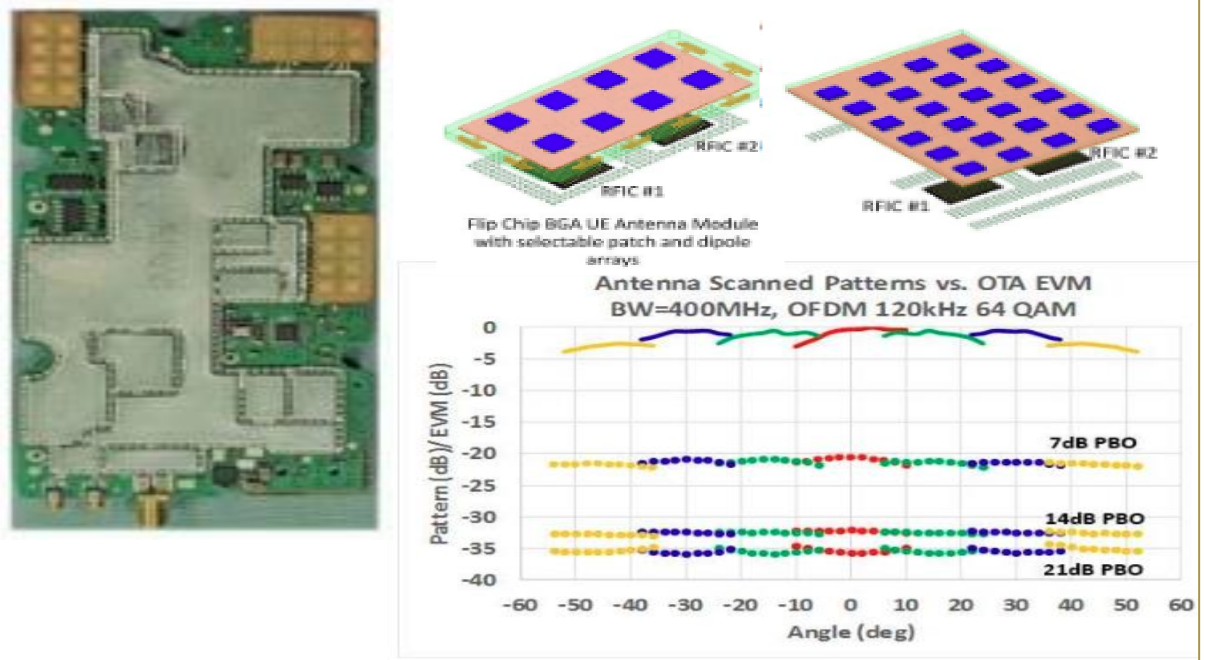
# High-Density Packaging: Chip-last mm-wave packages

## Organic laminates for Base-station (IBM)




- ✓ High bandwidth because of the air cavity
- ✓ Large-scale antenna array
- × Thick substrate with many metal layers
- × Mechanical reliability

## Organic laminates for UE (Qualcomm)



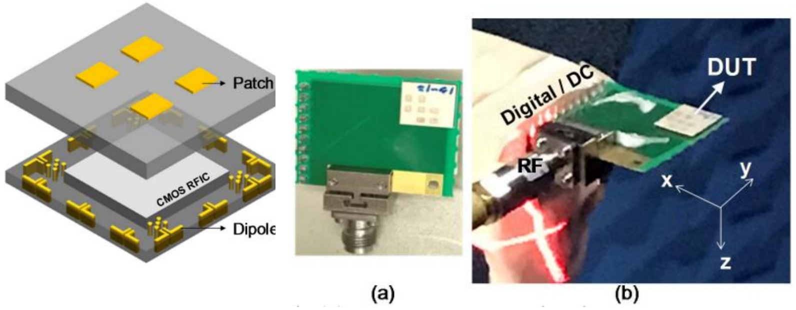

- ✓ Demonstration for handset AiP
- ✓ Co-design from CMOS through AiP
- × Thick substrate with many metal layers

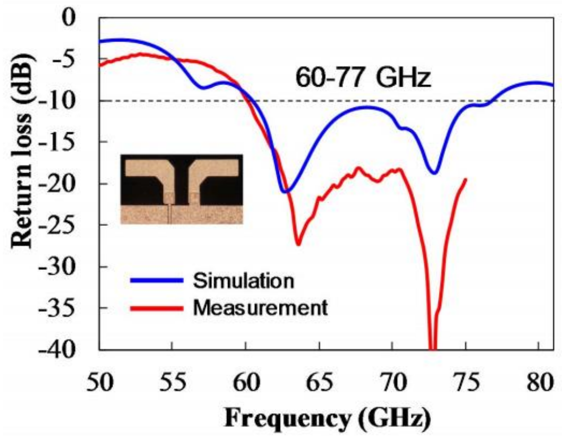


*(Slide from Atom Watanabe, GT-PRC)*

# *High-Density Packaging: Chip-first* mm-wave packages

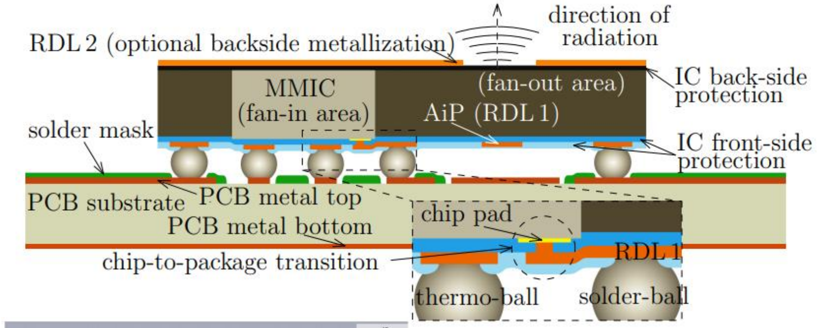
## InFO-AiP (TSMC)

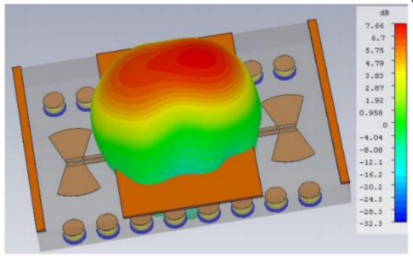


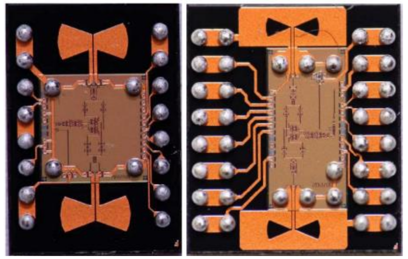



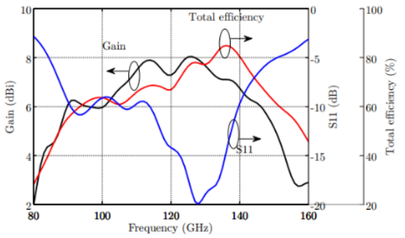

- ✓ Thickness reduction
- ✓ Low signal loss from Chip to Antenna
- × Unbalanced stack-up – Warpage
- × Patterning precision on molding compound

## eWLB (Infineon)



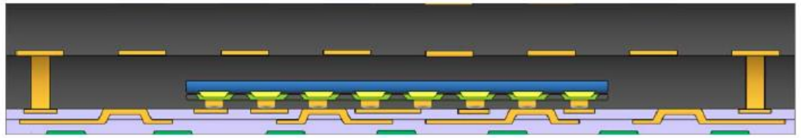








- ✓ Thickness reduction
- × Distance variation from Gnd to Patch
- × Patterning precision on molding compound

## Fan-out AiP (ASE)



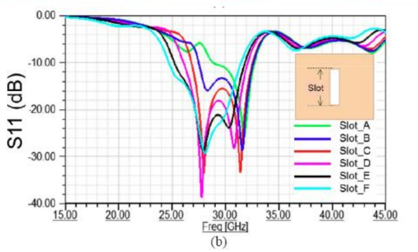



Fig. 11. Simulation result of various return loss by adjusting the dimension of notching slot structure.

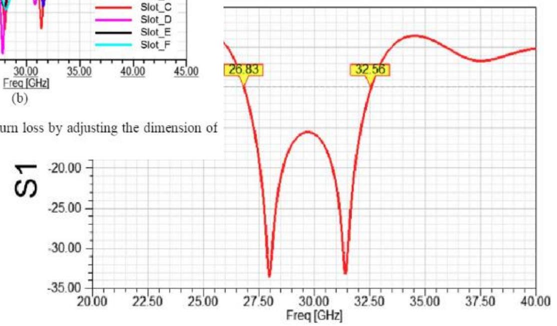



Fig. 12. Simulation result of stacking patch antenna

- ✓ Thickness reduction
- × High signal loss in through-mold vias
- × Mold-on-mold causes thickness variations



(Slide from Atom Watanabe, GT-PRC

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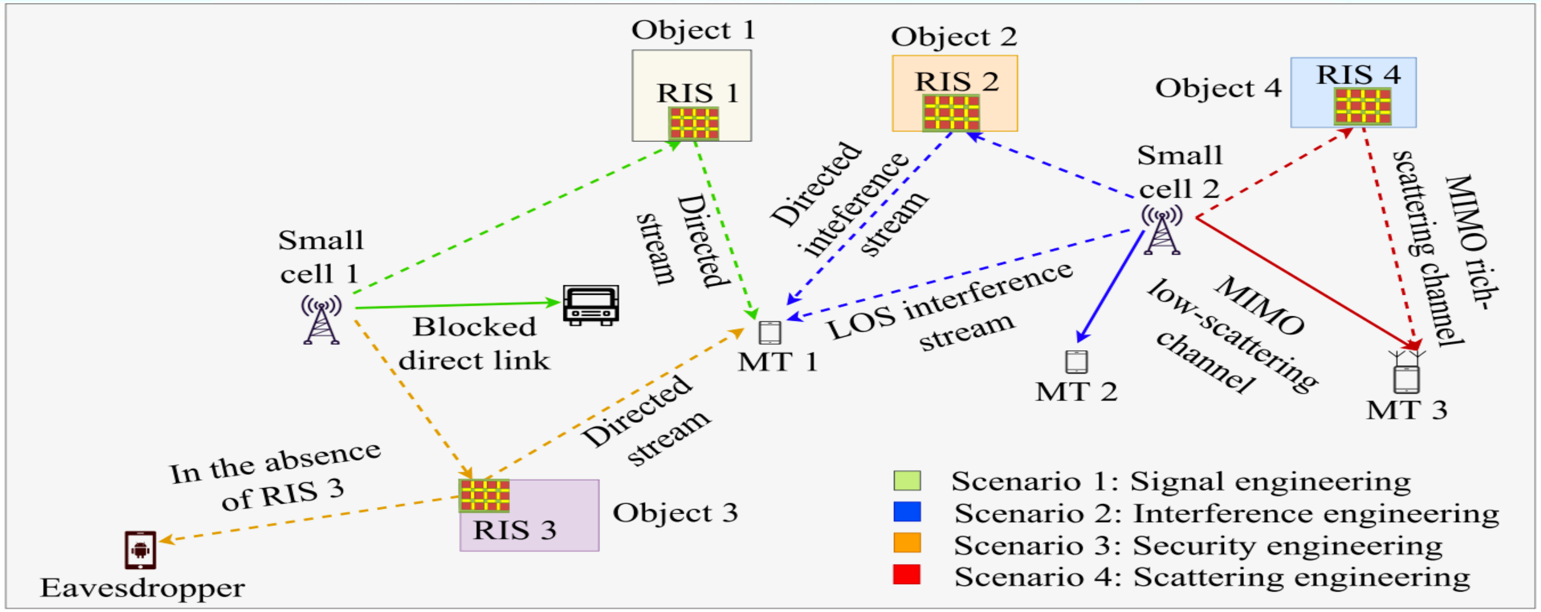
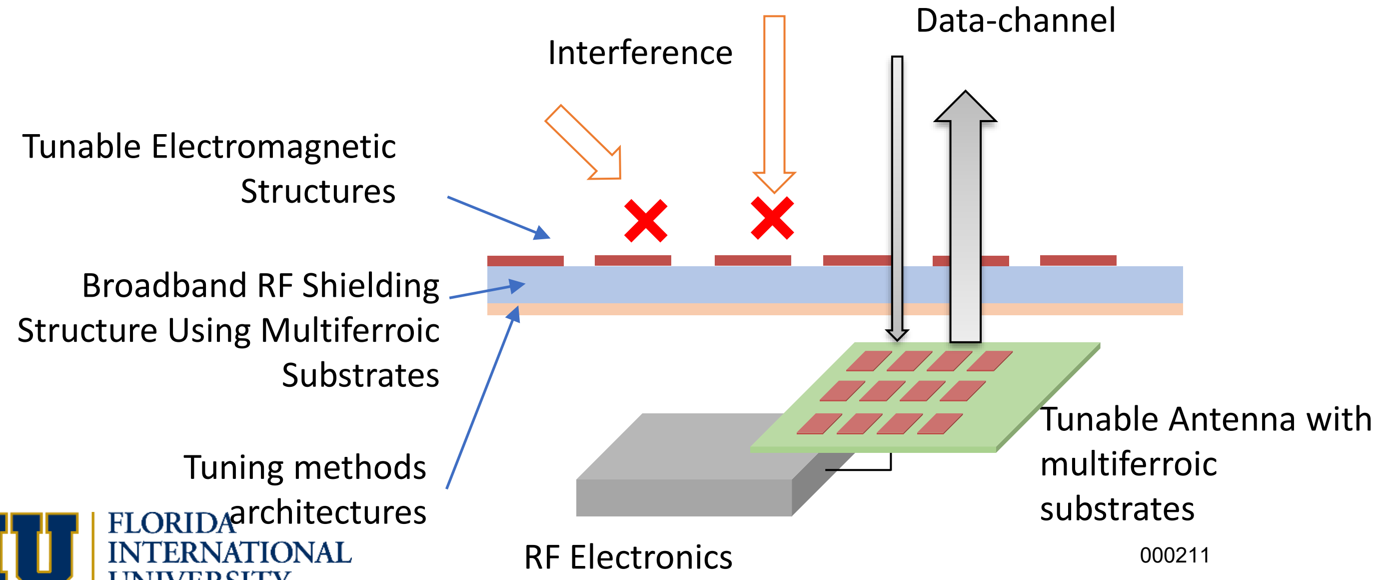
# Tunable or Smart FSS: Selected Examples

# Smart Environment with RIS

Need for new materials to achieve:

- Security from hacker / eavesdropper;
- Dynamic isolation from a nearby aggressor
- Able to steer the beam with metasurfaces
- Resistive cards to increase gain and bandwidth

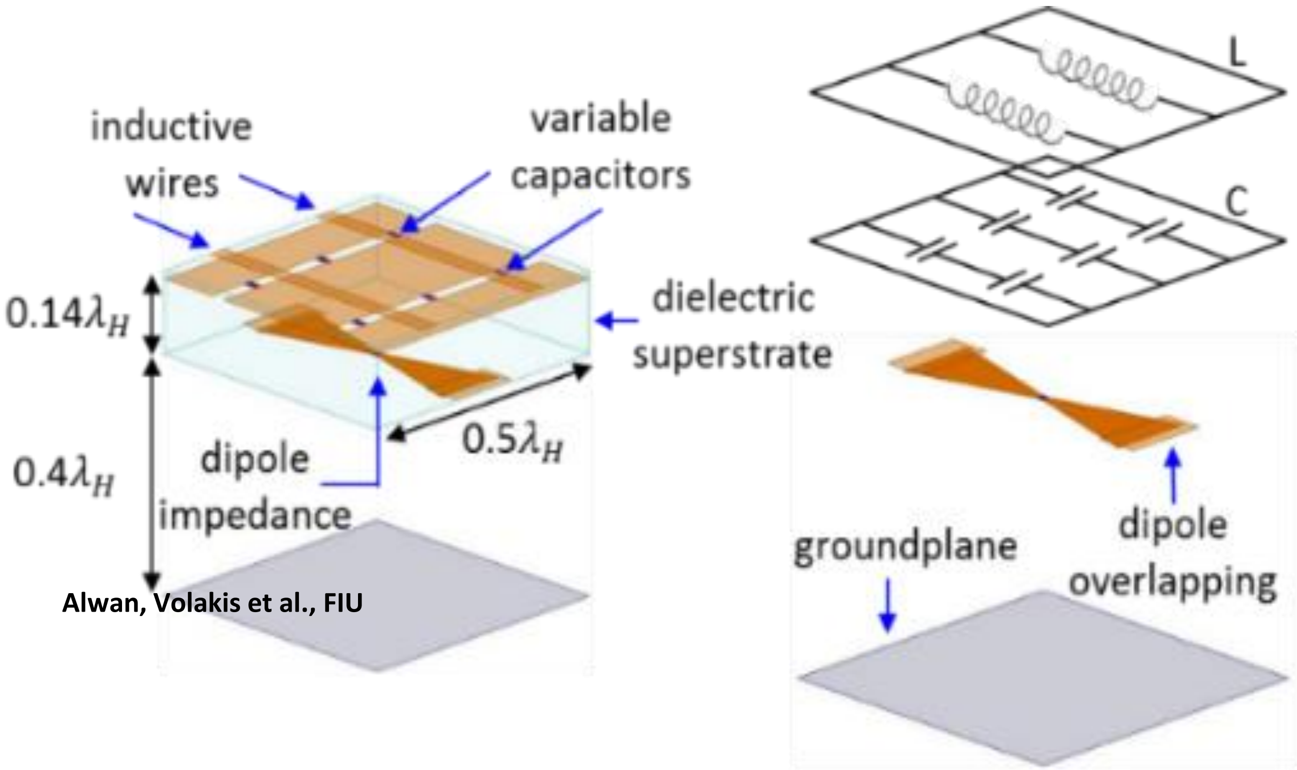


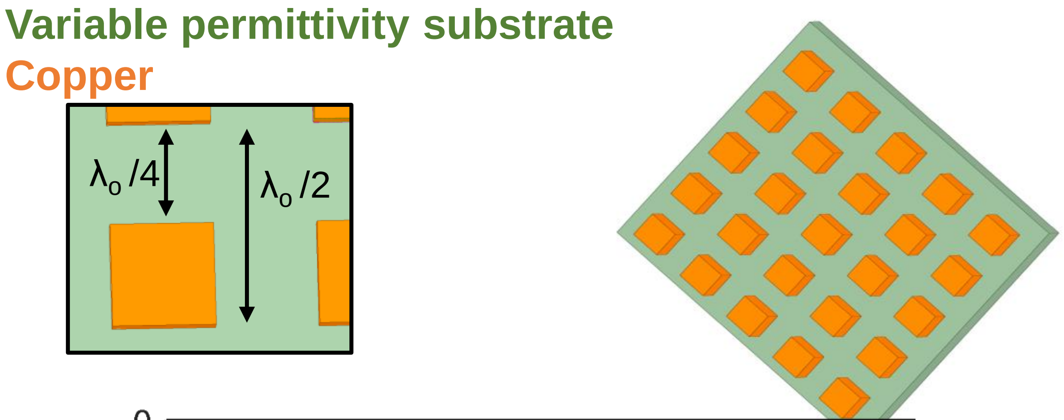

- ❑ *Multiferroic based electromagnetic architectures for smart shielding.*
- ❑ *Planar EM substrate architectures for smart substrates (with tunable permittivity) for antennas.*
- ❑ *Frequency selectivity and direction selectivity for EM blocking.*

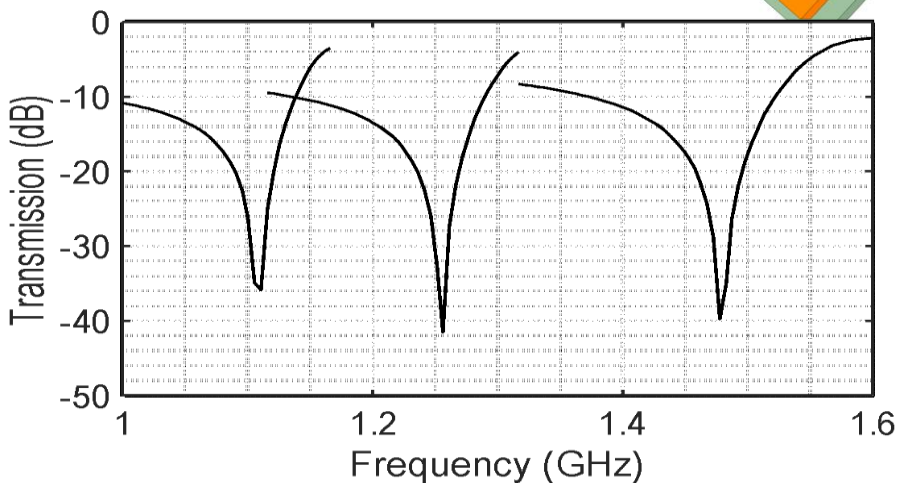
# Multiferroic Tunable Shields and Filters for Secure RF Electronics

**Reconfigurability with variable capacitors**



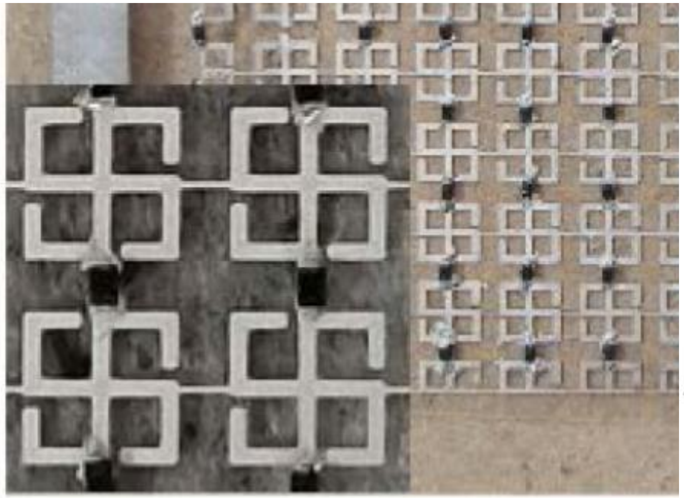

**Alwan, Volakis et al., FIU**

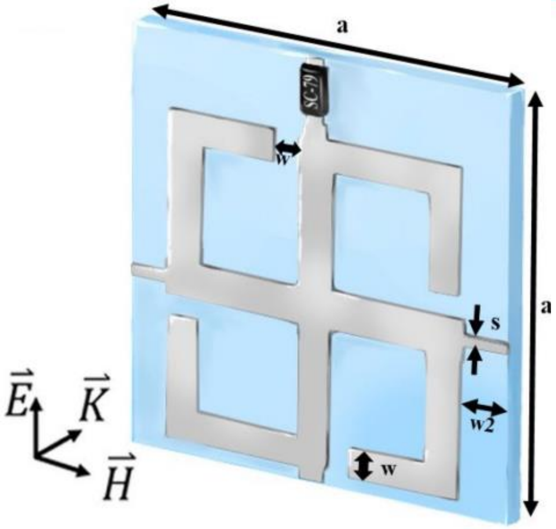


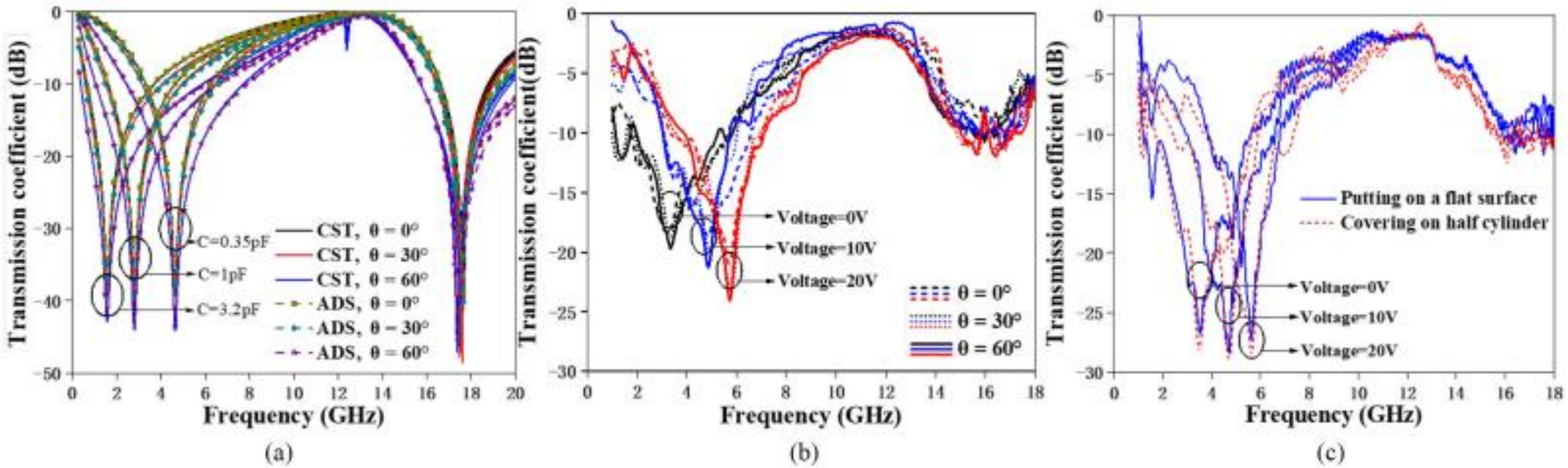

Reconfigurable metasubstrates using multiferroics
*Shubhendu Bhardwaj, FIU and UNL :*

# Tunable FSS with PIN Diodes



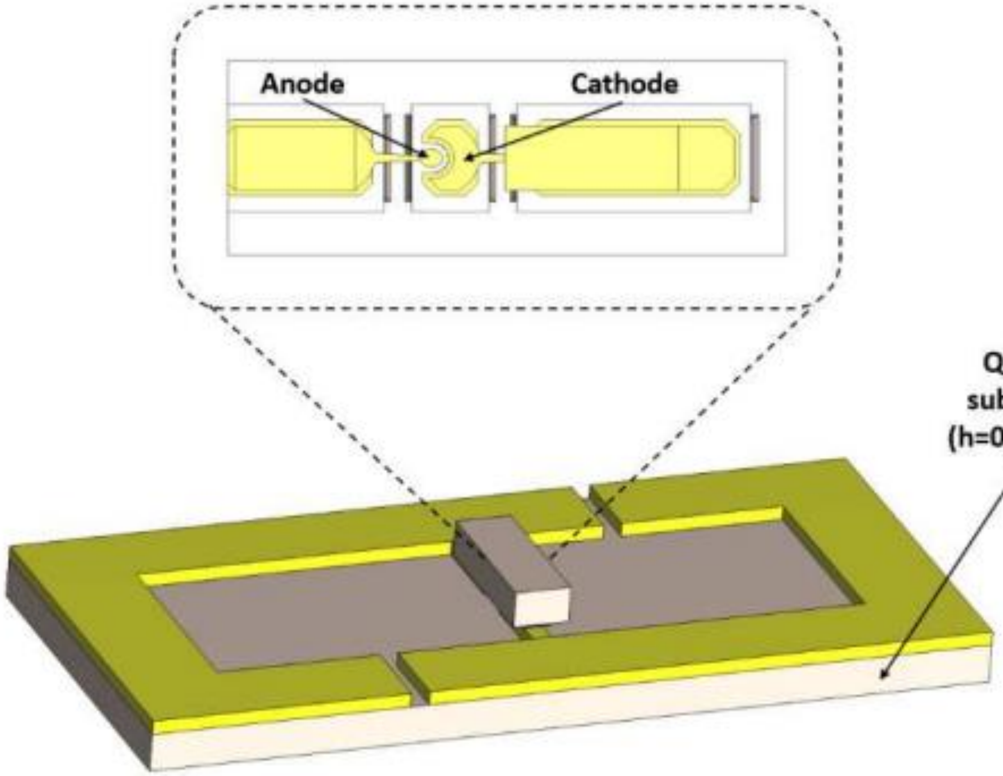


(a) Simulated transmission coefficient of the FSS varies with the tunable capacitance, under vertical polarized wave. θ is the angle of incident wave. Both CST and ADS are used as a comparison. (b) Measured transmission coefficient under different voltage bias by adjusting the tilted angle of the FSS sample by 0°, 30°, and 60°. (c) Measured transmission coefficient under different voltage bias in cases of putting it on a flat surface and covering on a half cylinder.




Safwan H. Ibrahim, Khalid S. Alsatti, Mohammed A. Hussaini, Jahanzeb Khan and Ghaffer I. Kiani
IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS, VOL. 19, NO. 12, DECEMBER 2020

# Tunable FSS with PIN Diodes



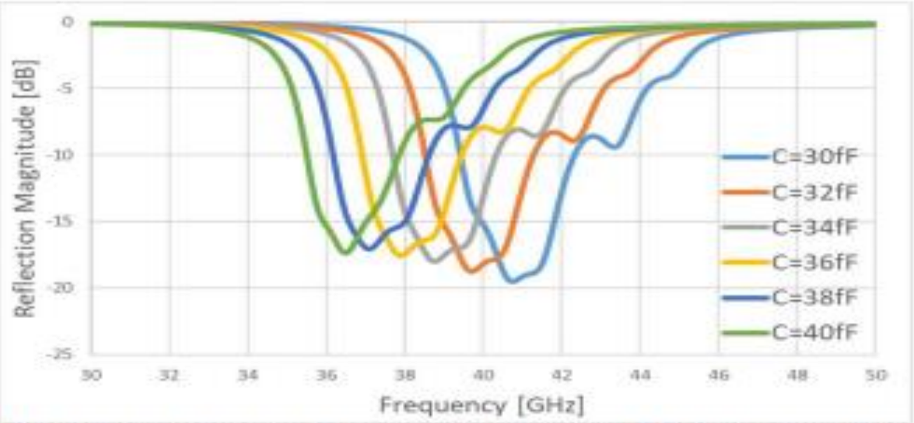




Fig. 8 The magnitude of the reflection coefficient (S11) for the active 5-layer FSS with Schottky diodes mounted and introduce the desired tuning.

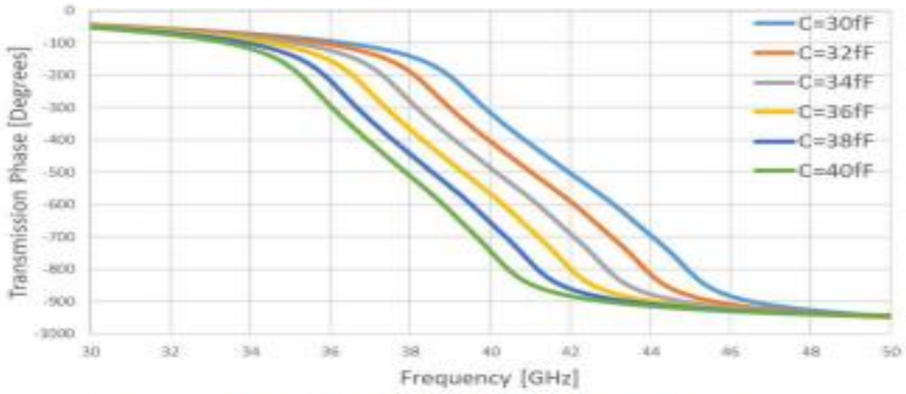


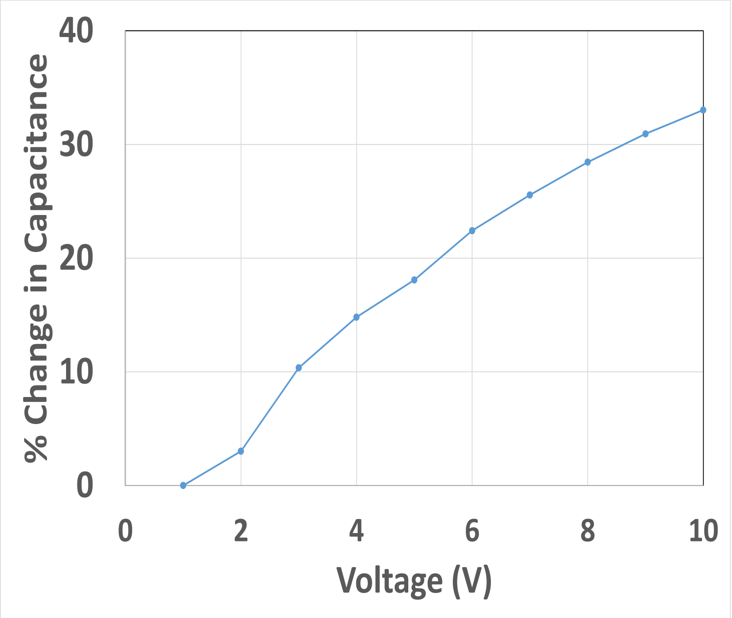

Fig. 9 The phase of the transmission coefficient (S21)for the active 5-layer FSS with Schottky diodes mounted and introduce the desired tuning.

Design of Tunable Millimetre-wave Pass-Band FSS Unit-Cell Loaded with GaAs Air-Bridged Schottky Diodes

Ioannis Gerafentis, Alexandros Feresidis, Metamaterials Engineering Group, School of Engineering, University of Birmingham, UK

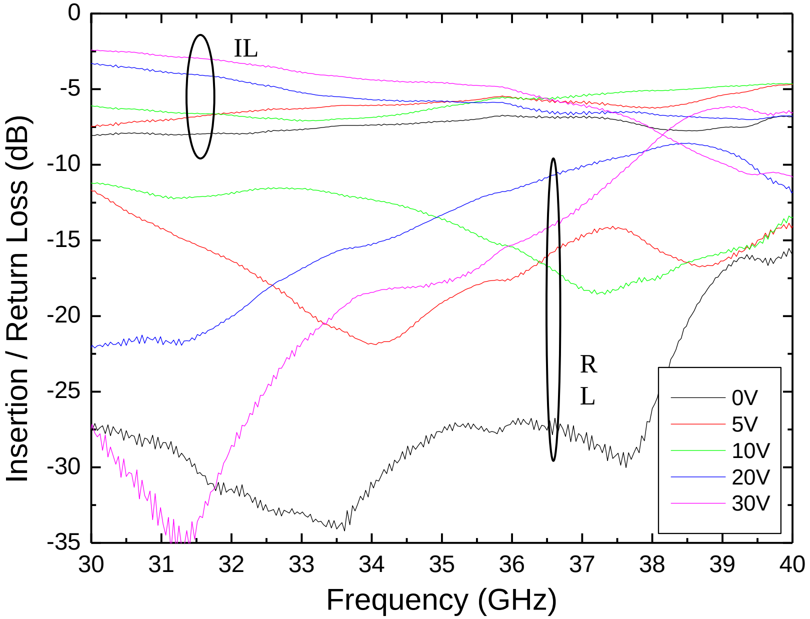
FIU Engineering & Computing
FLORIDA INTERNATIONAL UNIVERSITY

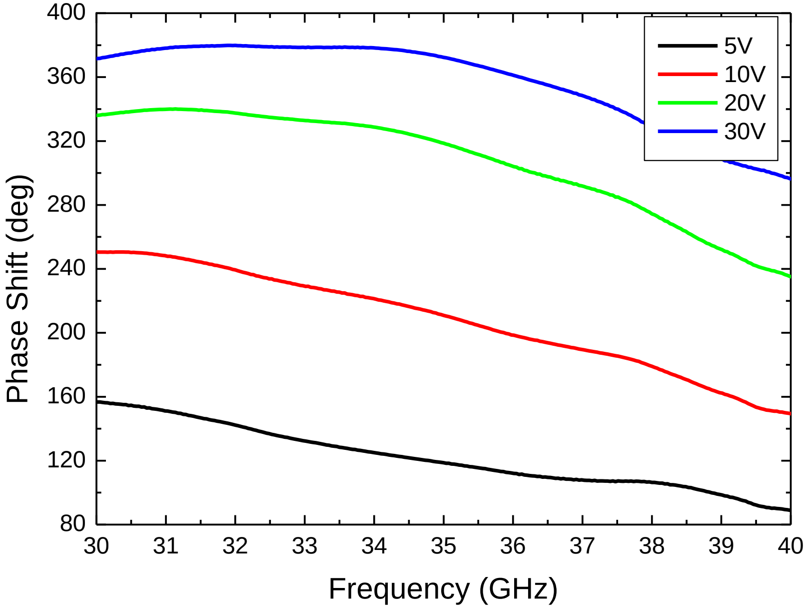
# Tunable Ferroelectric Dielectrics




## Phase Shifter–Ka-band Typical Performance

Ka-band Phase Shifter




Voltage-based tuning
Need voltages of 5 V/micron

***Courtesy of Andrew Hunt , n*Gimat Co., Norcross, Georgia**

# Tunable Liquid Crystal Dielectrics

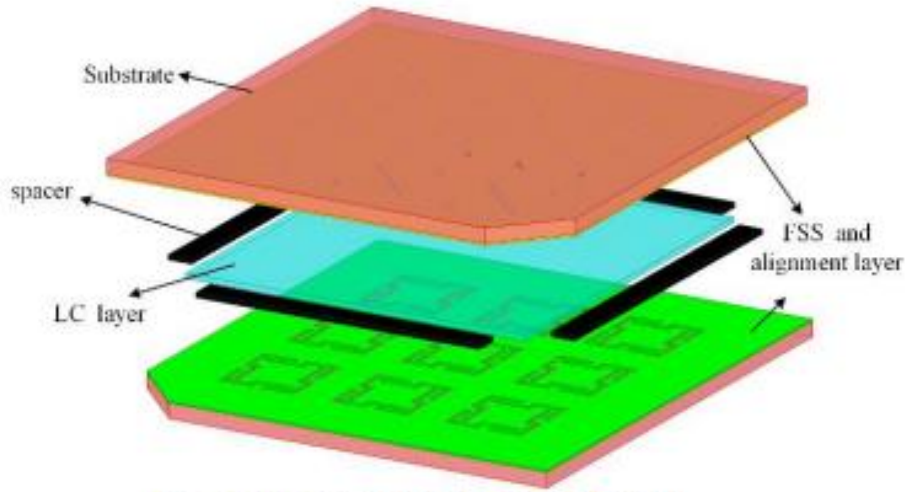
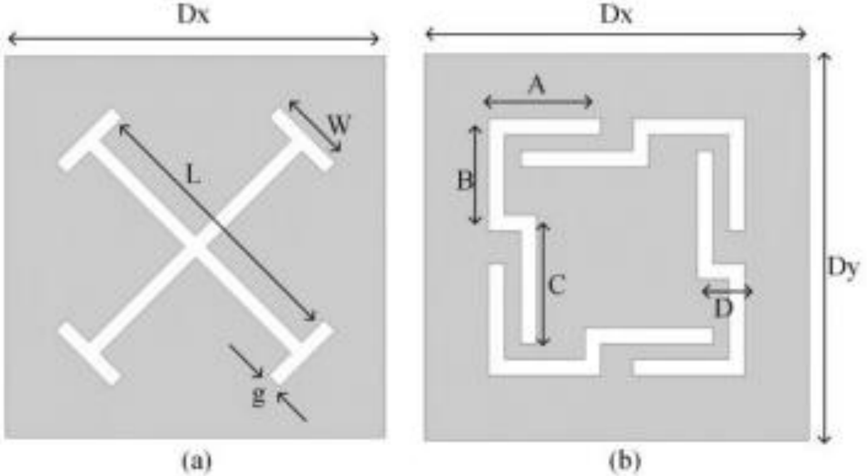



Fig. 1. Architecture of the LC-FSS.



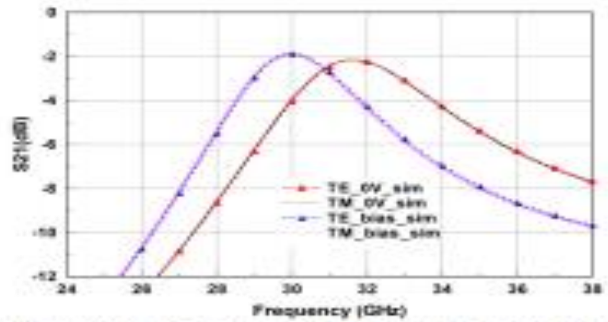




Fig. 3. Comparison of TE and TM polarization for bias and unbiased at normal incident angle.

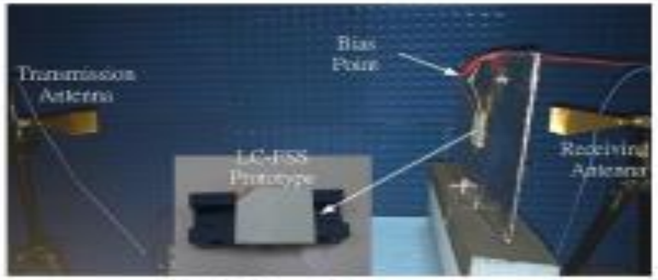



Fig. 4. Setup of measurements

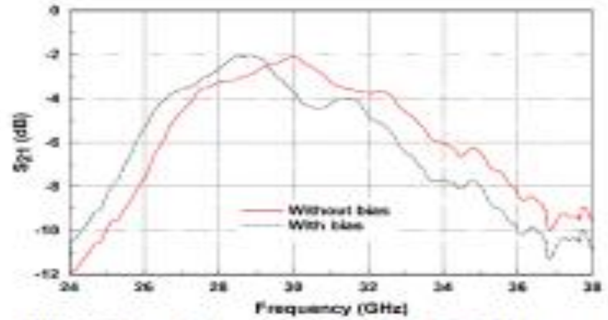



Fig. 5. Transmission response of the LC-FSS prototype with/without bias.

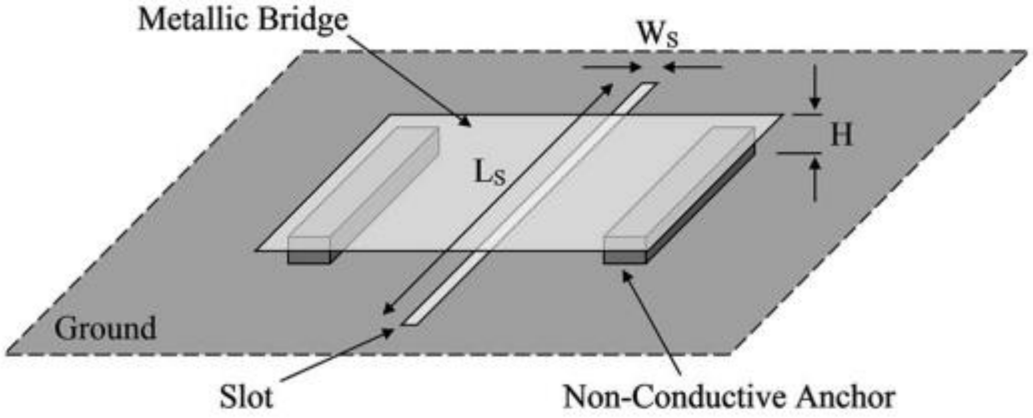
Tunable bandpass liquid crystal frequency selective surface resonating at Ka-band, which has a frequency tunability, closed to 5% of its center frequency.

LC-FSS prototype was fabricated by normal print circuit board (PCB) technology and a Merck-E7 LC material.

Tunable Frequency Selective Surface (FSS) based on LC Material for mmWave Communications

Cheng-Chung Lin, Guo-Sheng Lin, Guan-Jhou Ke, and Hsi-Hsir Chou, National Taiwan University of Science and Technology

# MEMS-Based Tunable FSS



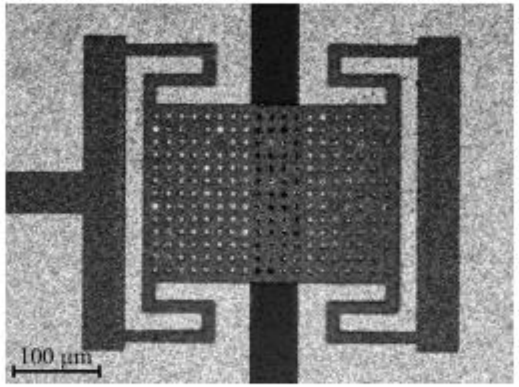




Fig. 9. Picture of the fabricated MEMS bridge.

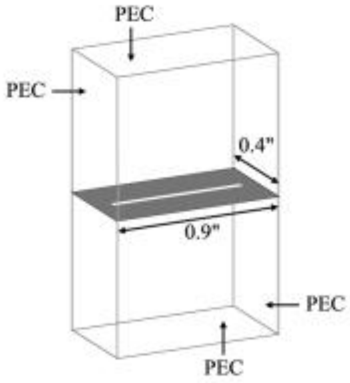



Fig. 10. FSS unit cell simulation setup.

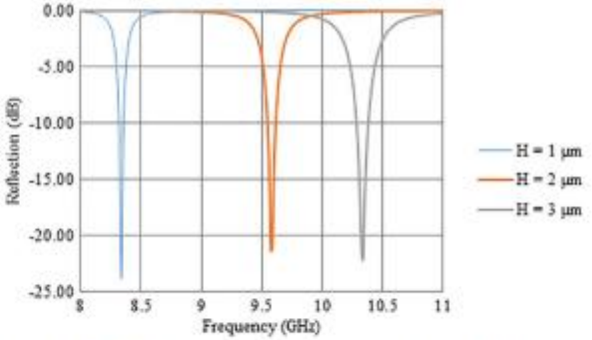



Fig. 11. Simulated response of the FSS unit cell vs. height of the MEMS bridge.

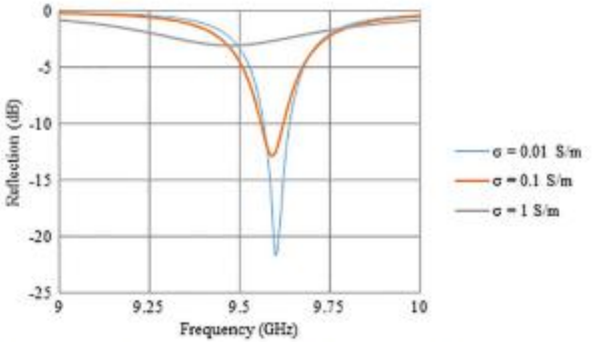
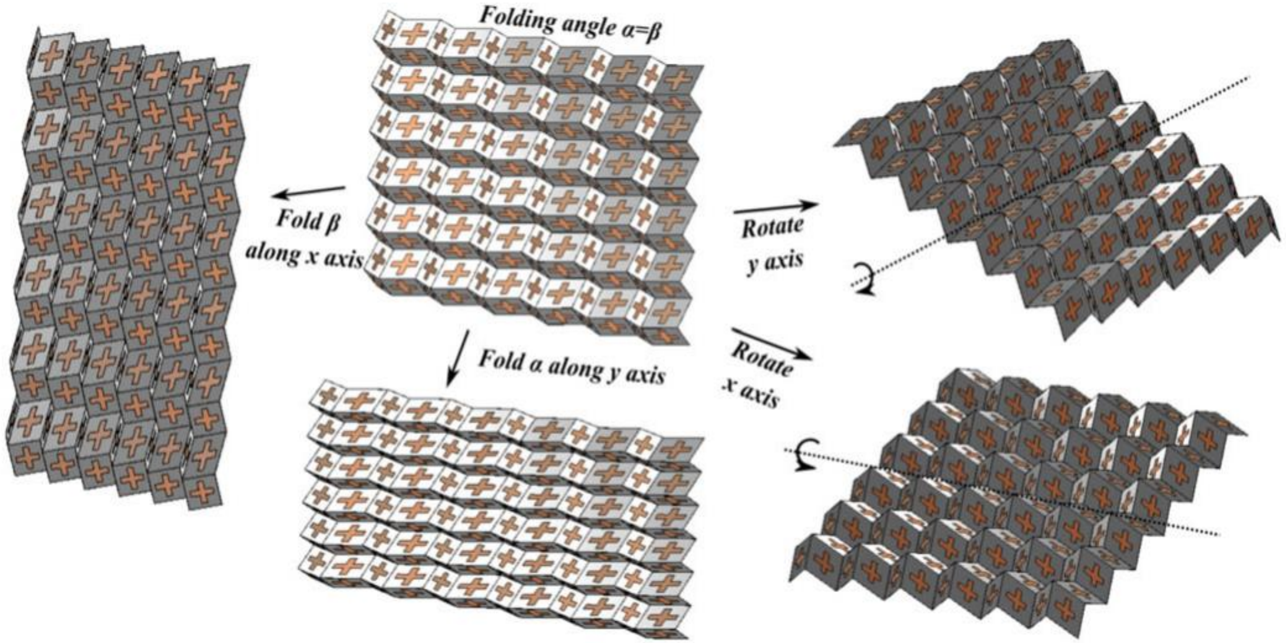


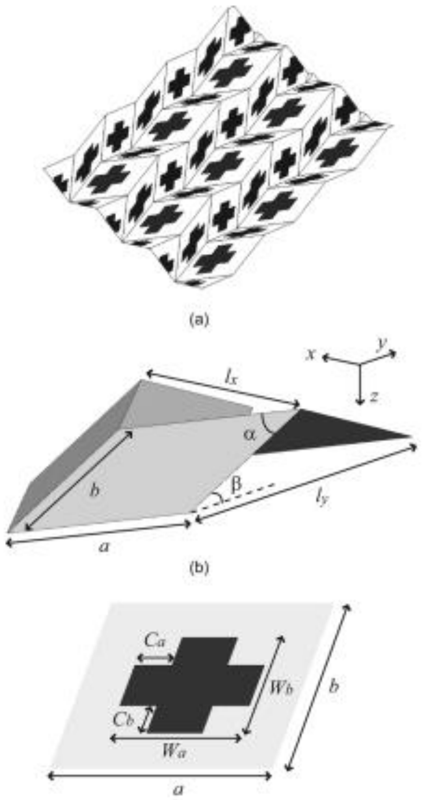

Fig. 12. Simulated response of the FSS unit cell vs. conductivity of silicon anchors 4 $\mu m$ in height.

**Tuning of the resonance frequency is achieved by using a metallic MEMS bridge over the slot. The bridge acts as a capacitive load, increasing the equivalent capacitance, and so decreasing the resonance frequency.**

X-Band Tunable Frequency Selective Surface Using MEMS Capacitive Loads
Mojtaba Safari, Cyrus Shafai, and Lotfollah Shafai
IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 63, NO. 3, MARCH 2015

# Origami-Based Reconfigurable FSS



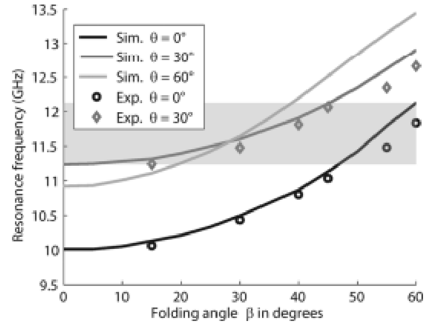




Fig. 3. Simulated and measured resonance frequencies, $f_{res}$, in GHz.

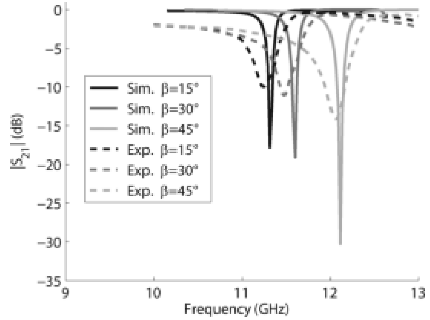



Fig. 4. Simulated and measured transmission coefficient $|S_{21}|$ at oblique incidence at $\theta = 30°$.

A novel 4-DOF wide-range tunable frequency selective surface using an origami "eggbox" structure, Cui, Bahr, Tentzeris

Yepu Cui , Ryan Bahr, Samantha Van Rijs and Manos Tentzeris
International Journal of Microwave and Wireless Technologies

Origami Tunable Frequency Selective Surfaces

IEEE ANTENNAS AND WIRELESS PROPAGATION LETTERS
VOL. 11, 2012

FIU Engineering & Computing
Florida International University

# Summary

- **mmWave MIMO with beam-forming (at base stations)** to play a critical role toward 6G
- **RIS** critical for the urban environment:  individual phase control
- **In-band full-duplex** is an enabling technology that will play a key role in building 6G
- **UWB antennas** with different antenna designs, coupled with broadband feeding networks
- **Embedded** filters, power dividers, isolation via arrays and solid copper surfaces, impedance-matched interconnects: advanced design rules are needed
- **Tunable FSS** for attaining selective isolation and beamsteering effects