Towards Wide-Angle Scanning and Reconfigurable Wideband Arrays

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Presentation Outline

- Introduction + motivation
- Reconfigurable Reflectarray
- Wide-angle Scanning Phased Array
- Summary and Future / Ongoing Work

Introduction – Antenna Team @ RE Group, UOulu

– Research Interests
  - Broadband/wideband/compact antennas
  - Reconfigurable/multifunctional antennas and surfaces
  - Coupling mitigation, matching and interface to RFEs
– Team: ~14 FTEs: 1 Professor, 1 Academy Fellow, 1 postdoc, 9 doctoral researchers, 2 project researchers. Others: 1 Ext. Research Fellow, 1 Ext. Project Researcher
– Examples of Research Activities
  - Wideband /multiband arrays for base stations
  - Reconfigurable antennas for antennas and surfaces
  - Multifunctional metasurfaces (e.g. beamsteering and absorption)
  - Compact antennas for wearable devices
  - Lens antennas and feed designs (sub-THz band)
  - Reflecting amplifiers for reconfigurable surfaces

Introduction

- NextG/5G/6G systems need antennas with high gain, wide bandwidth, and preferably beamsteering.
- Existing designs often face (relatively) narrow bandwidth, scan loss, and results in non-planar profile, and complex feeding.
- Thus, two solutions are investigated, targeting practical, low-complexity, better performance antennas:
  - Reconfigurable reflectarrays based on magnetoelectric (ME) dipole – to offer wideband and simple electronic beam control.
  - Wide-angle phased arrays based on the connected slot array (CSA) concept – to offer dual polarized array for potential 5G-NR FR1 base stations.

Arrays and Their Feeds

- Phased arrays feeds the element directly, typically with predefined phase (difference)

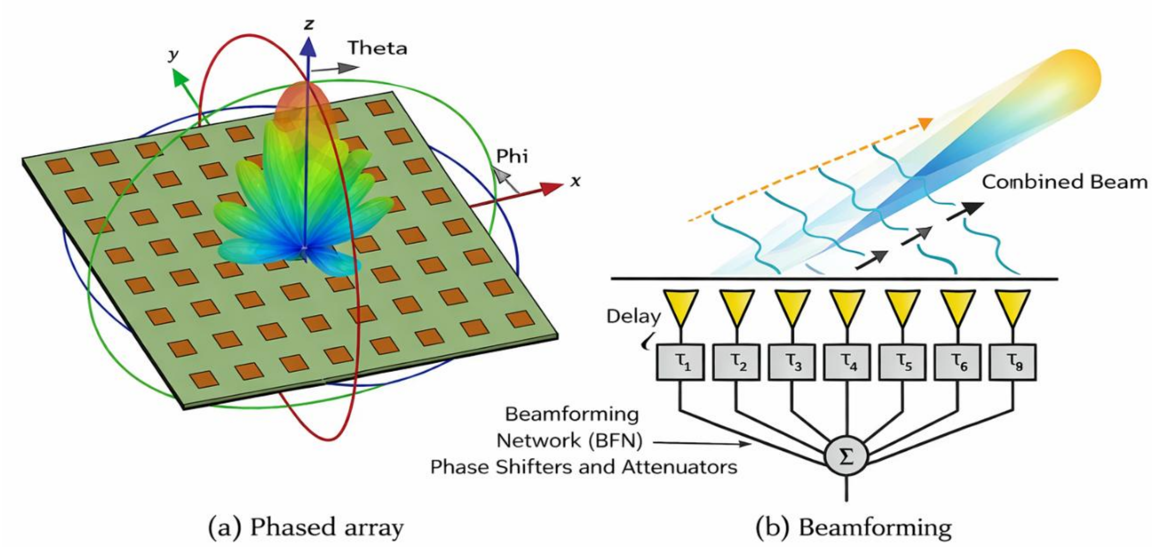

Fig. (a) Phased array (b) Beamforming [1], [2].

https://www.keysight.com/blogs/en/tech/sim-des/designing-phased-arrays-key-principles-challenges-and-solutions

- Reflectarrays uses single feed at NF. Phase shifted reflection produced from the array element/surface

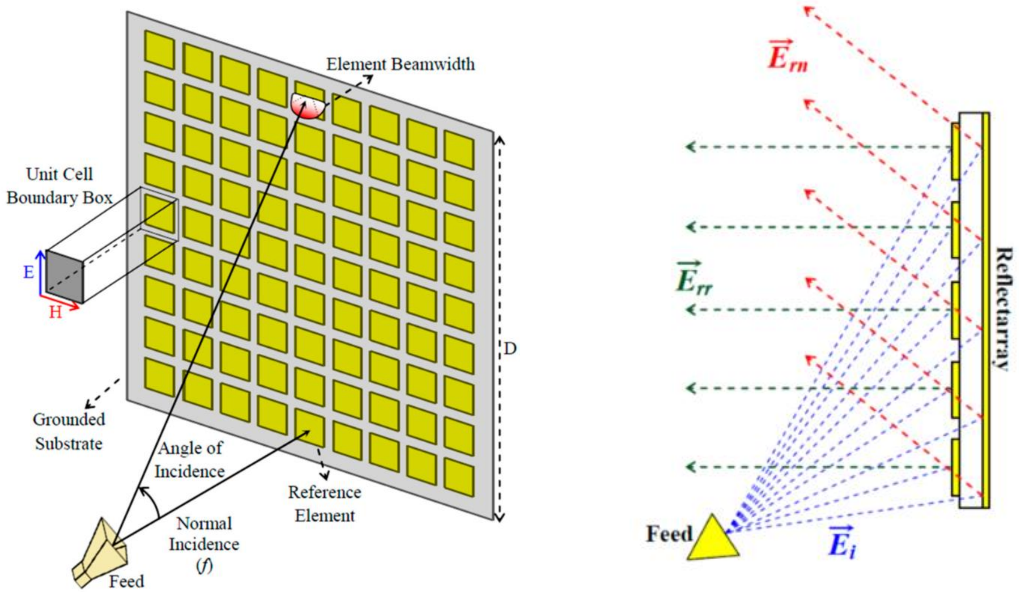

Fig. (a) Reflectarray (b) Reflection of the incident signals from the surface of the reflectarray [3].

Dahri, M. Hashim, et al. "Aspects of efficiency enhancement in reflectarrays with analytical investigation and accurate measurement." *Electronics* 9.11 (2020): 1887.

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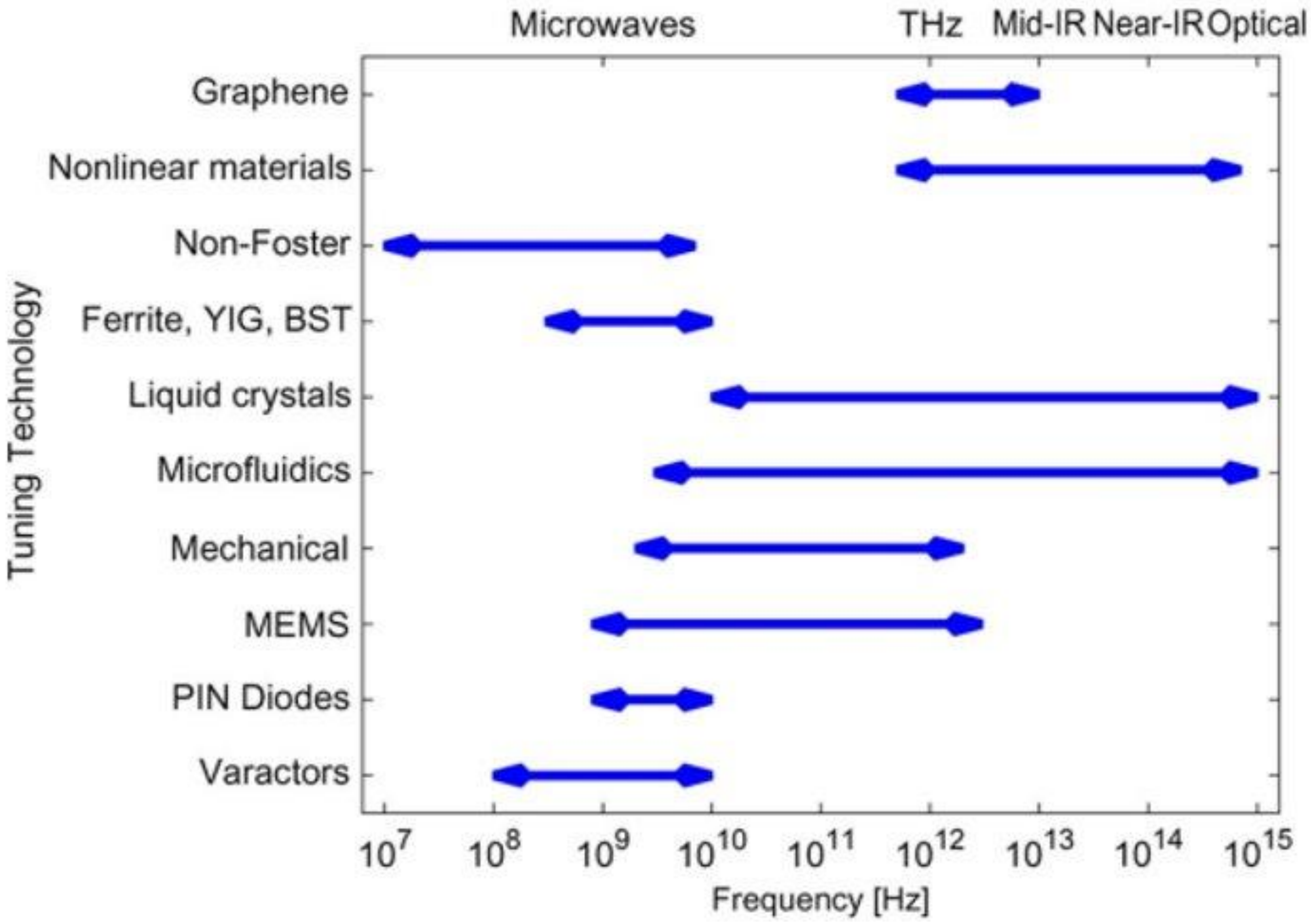
Antenna Tuning Technologies

- Types of Reconfiguration:
  - Frequency
  - **Beam**
  - Polarization or
  - Compound (their combination)

- Methods /Technology:
  - **Electronics** (**PIN diodes**, varactors)
  - Mechanical (microfluidics, MEMS)
  - Materials, etc



G. Oliveri, D. H. Werner, and A. Massa, “Reconfigurable electromagnetics through metamaterials-a review,” *Proceedings of the IEEE*, vol. 103, no. 7, pp. 1034–1056, Jul. 2015, doi: 10.1109/JPROC.2015.2394292.

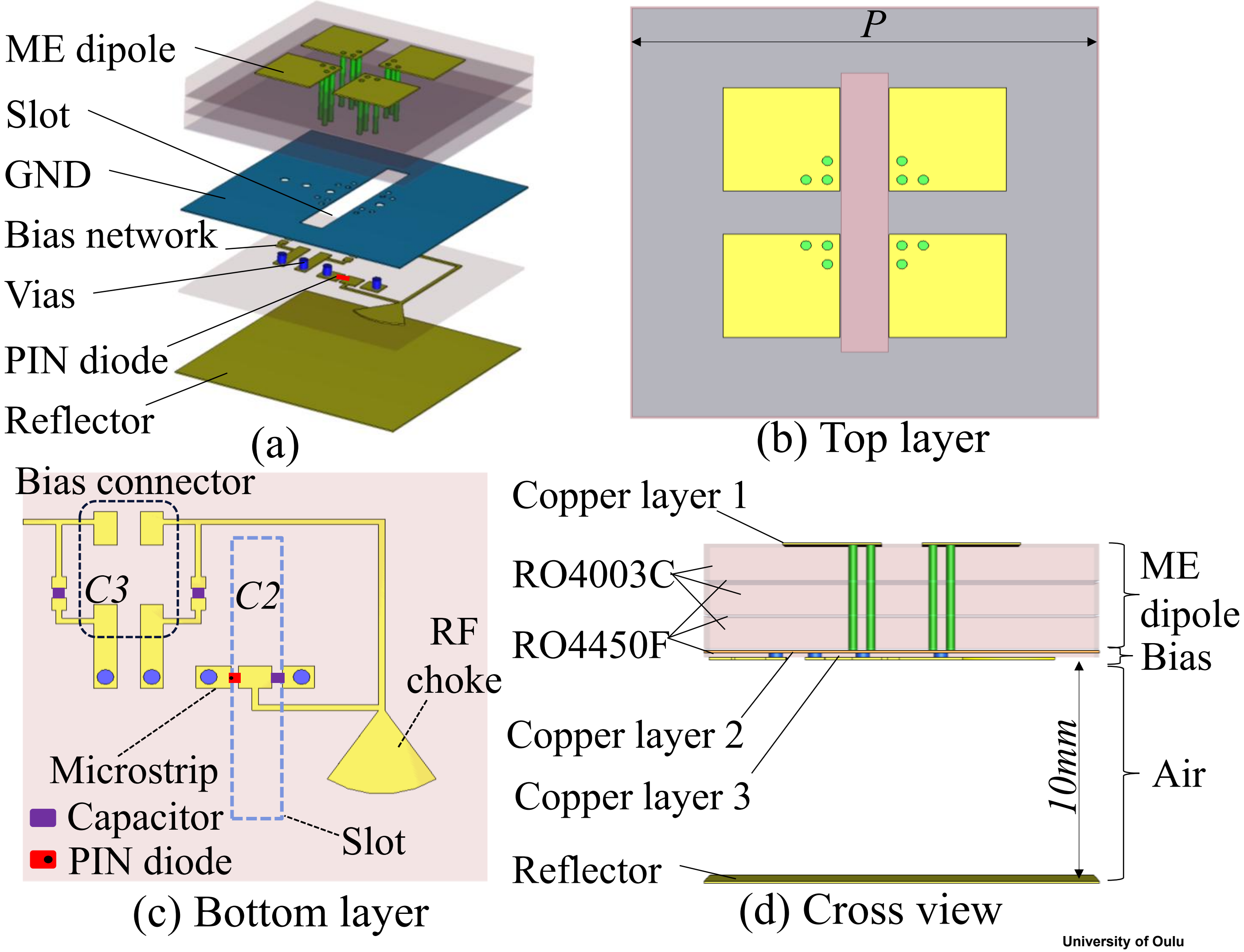
Wideband Reconfigurable Reflectarrays

Target Specifications

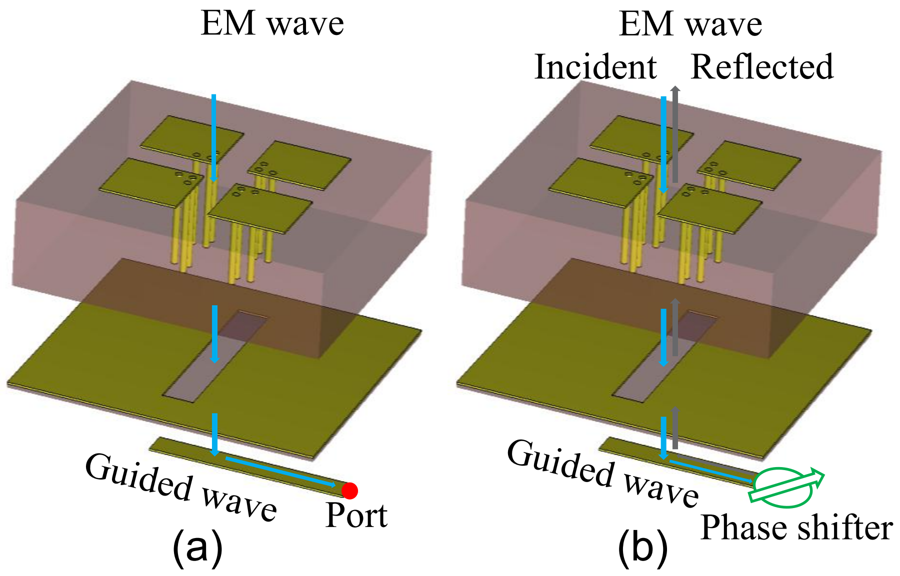
- Frequency: min 6.4 – 7.1 GHz (Study band for 6G, modest FBW target of ~10 %)
- Polarization: Single, linear polarization
- Reconfiguration: 1-bit PIN diode / UC
- Beam Scanning: min >±40°

Unit cell design

- UC profile: 22 x 22 x 5 mm^3 (~ 0.5λ x 0.5λ x 0.11λ at 6.75 GHz)
- Sub. material: RO4003C (3 layers)
- Bonding material: R4450F
- PIN diode: MACOM MADP-000907-14020P

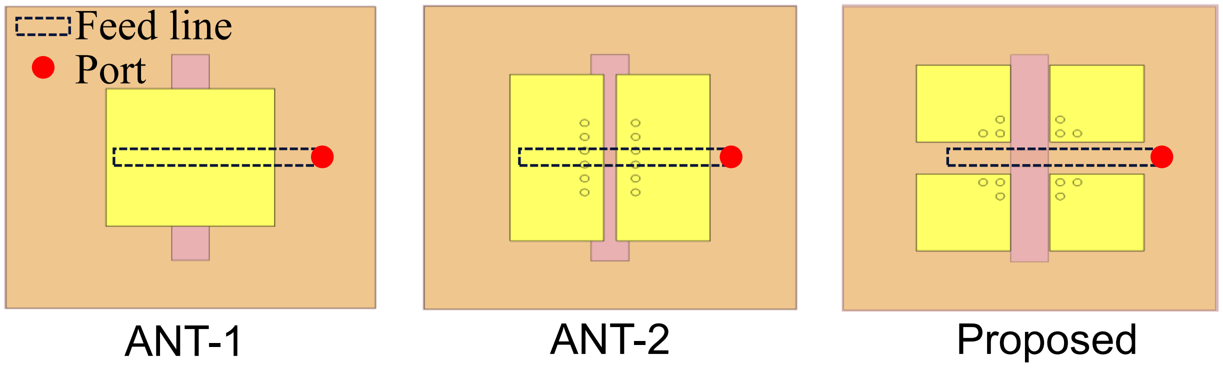


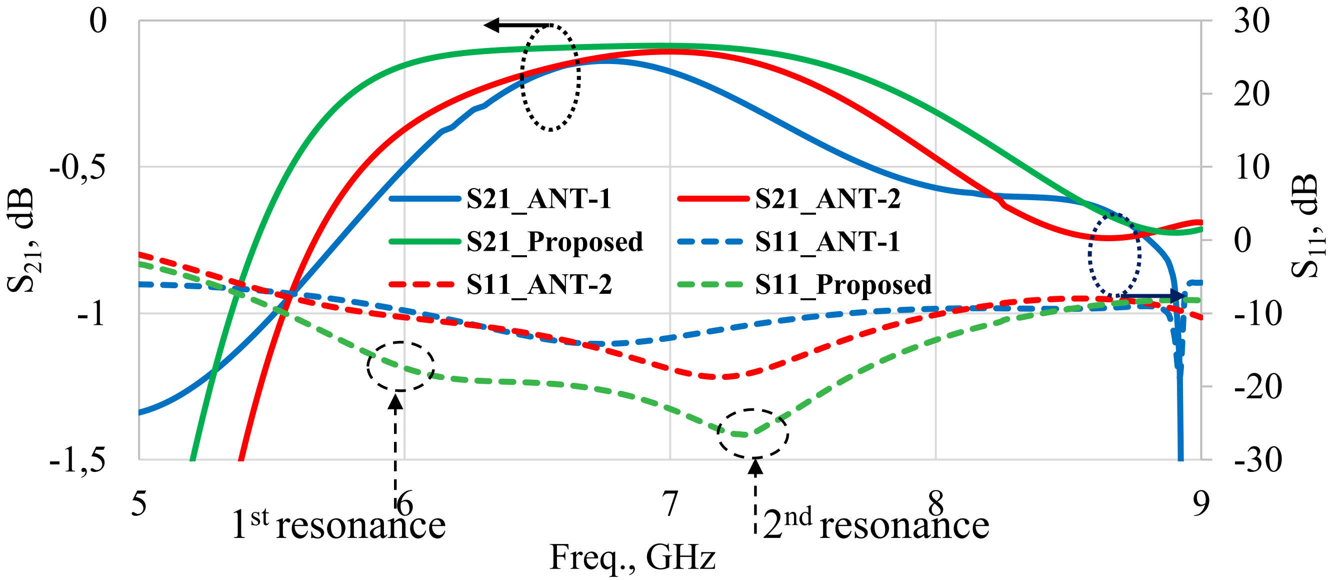
Radiating element design



Guided wave principle: a) Aperture-coupled ME antenna. b) Reflective aperture-coupled ME element

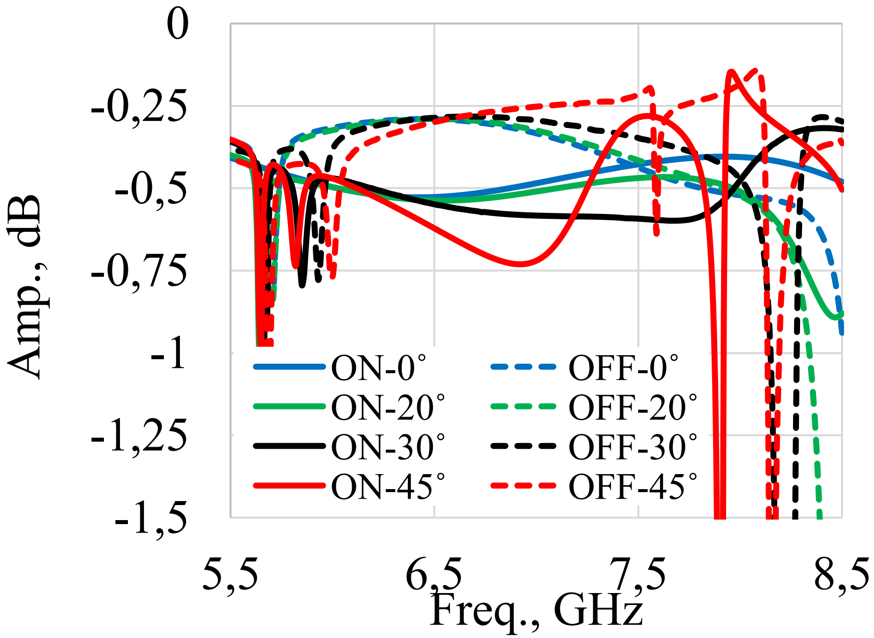
- S21 ≥ -0.5 dB and S11 ≤ -10 dB:
  - ANT-1: 24.3% (6.06 GHz to 7.74 GHz).
  - ANT-2: 31.6% (5.86 GHz to 8.06 GHz).
  - Proposed: 40.1% (5.56 GHz to 8.35 GHz).



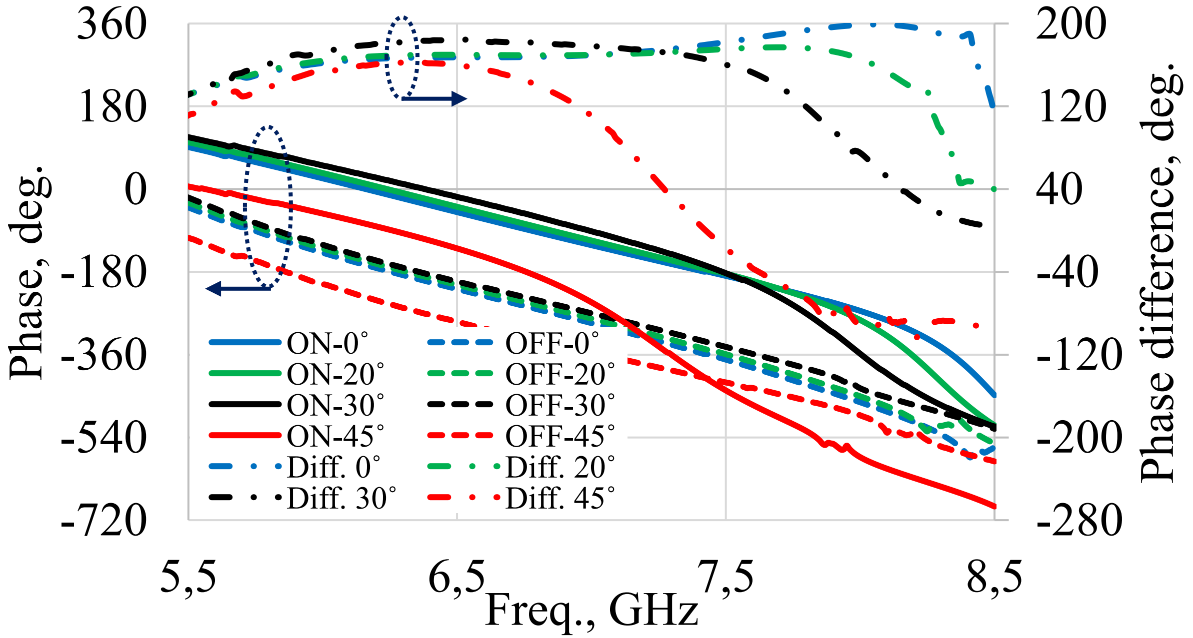


(f) Reflection and transmission coefficients

UC simulation results



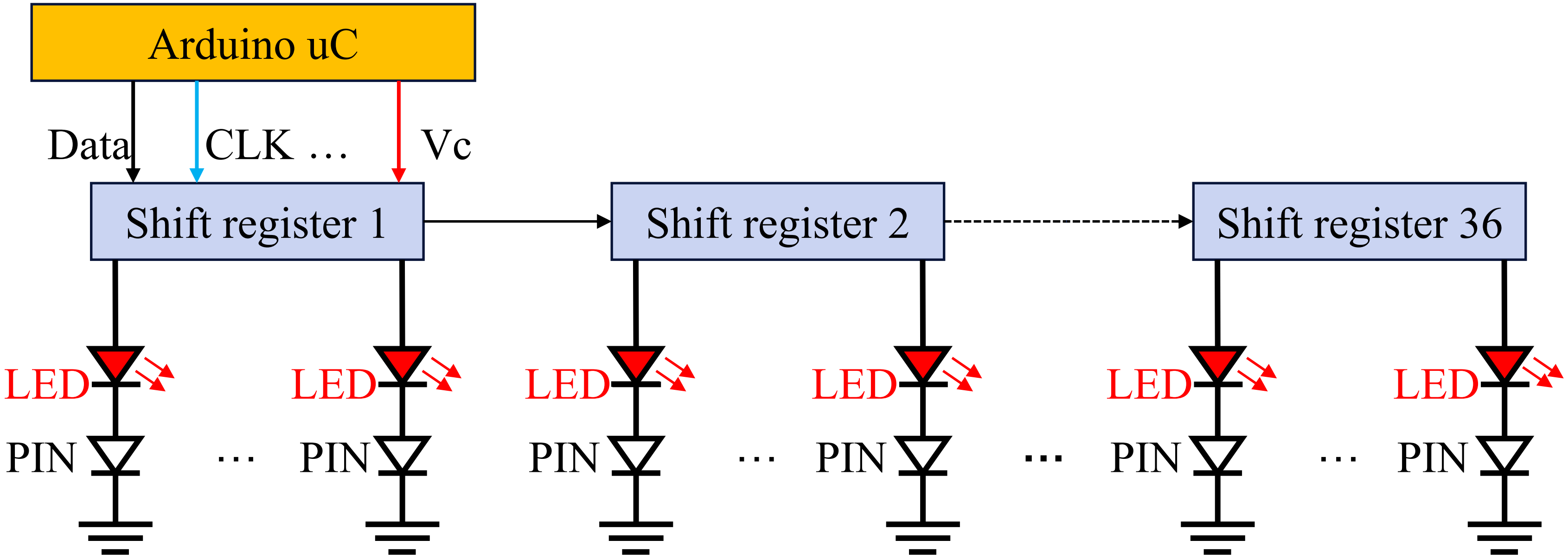
(a) Amp. responses

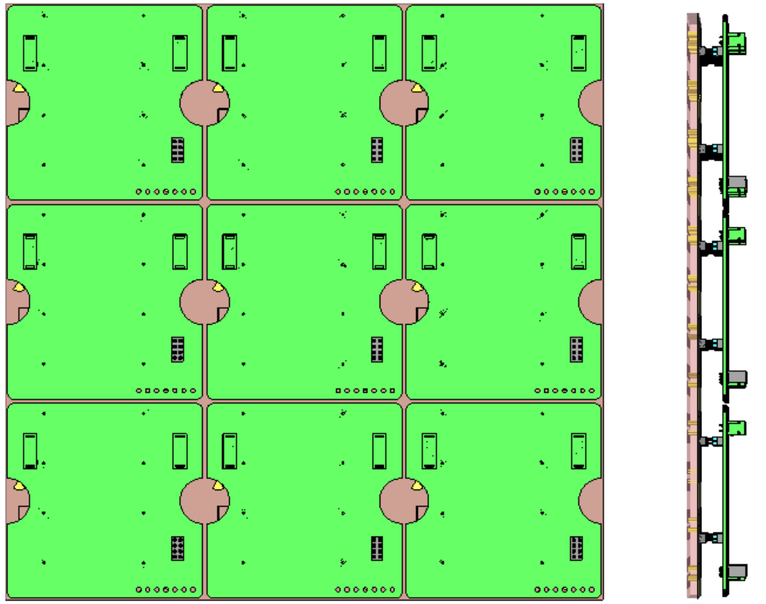


(b) Phase responses

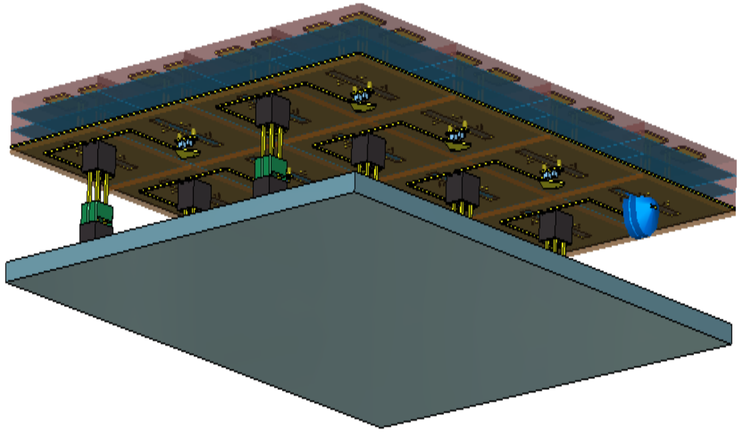
- 1-bit phase shift (180° ± 20°): 35% from 5.9 – 8.4 GHz under normal incidence.
- At 20° incidence, phase bandwidth is 31.4% (5.9 – 8.1 GHz).
- At 30° incidence, phase bandwidth is 26.2% (5.76 – 7.5 GHz).
- Reflection loss ≤ 0.8 dB for all incidence angles.

Beam control





Control board

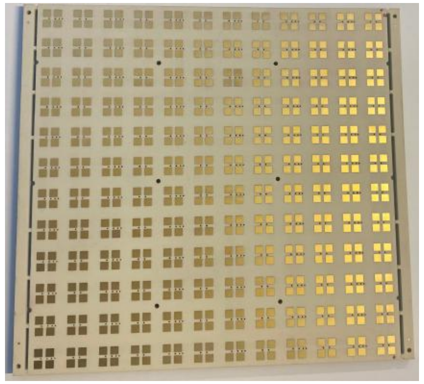


1 sub-control board and antenna

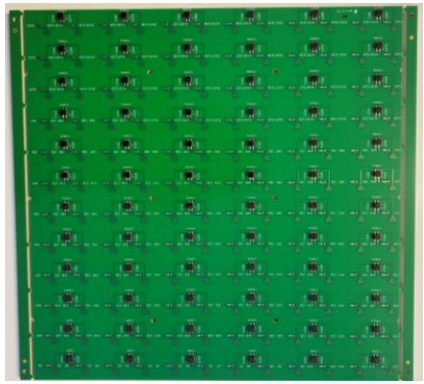
- Array 12 x 12 UCs: 36 shift registers in daily-chained configuration, each controls 4 PIN diodes.
- Arduino ↔ Shift register on the control board ↔ PINs' states on the ANT board → Beam control.
- 9 sub-boards for easier installation + potential scalability.

M. Abdullah, et al, "Control Board Design Strategy Towards Scalable and Intelligent RISs," *20th EuCAP 2026,* Dublin, Ireland, 19 - 24 April 2026, accepted, to appear

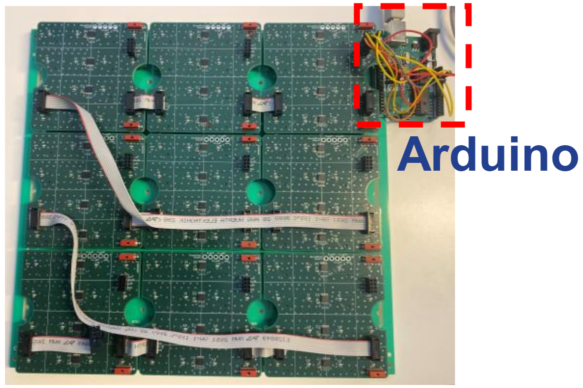
12x12 Array prototype



ANT layer
(Top)



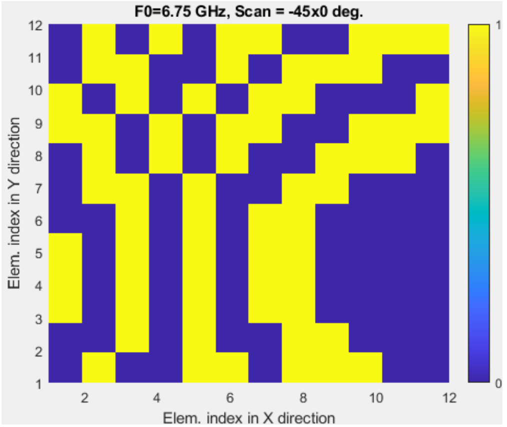
Biasing layer
(Bottom)

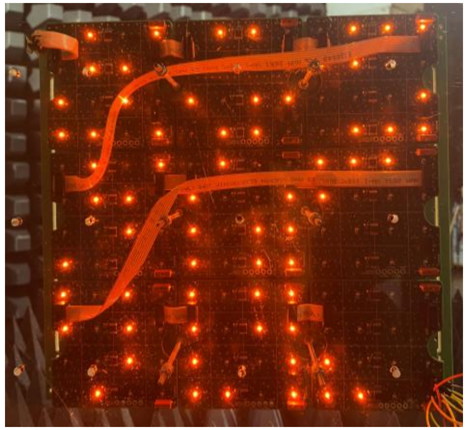


Control layer

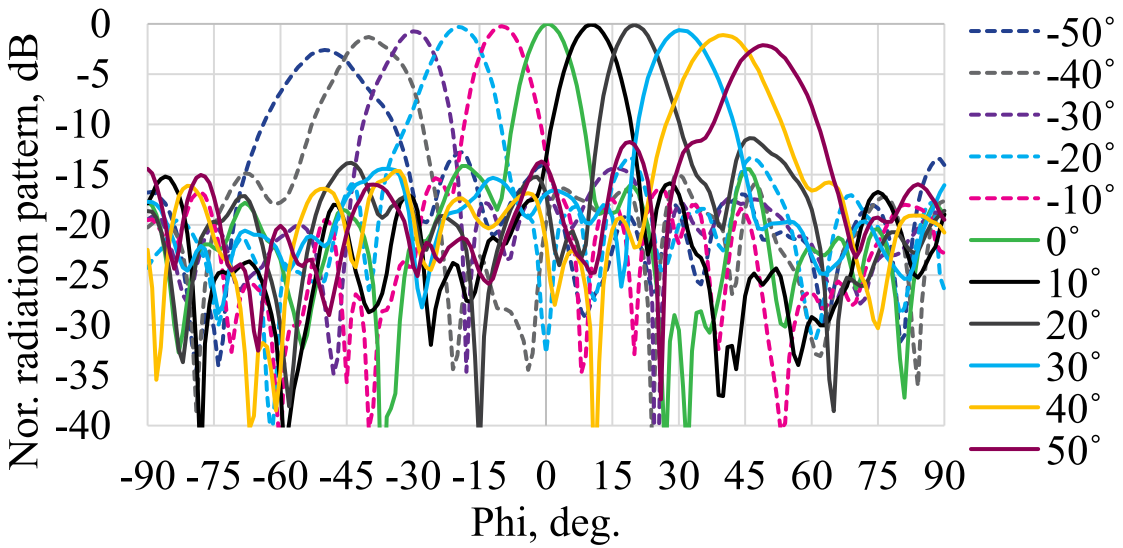
MATLAB → Arduino → Control board → PIN ON/OFF with LED display.

- Phase ‘0º’/ ON stage
- Phase ‘180º’/ OFF stage

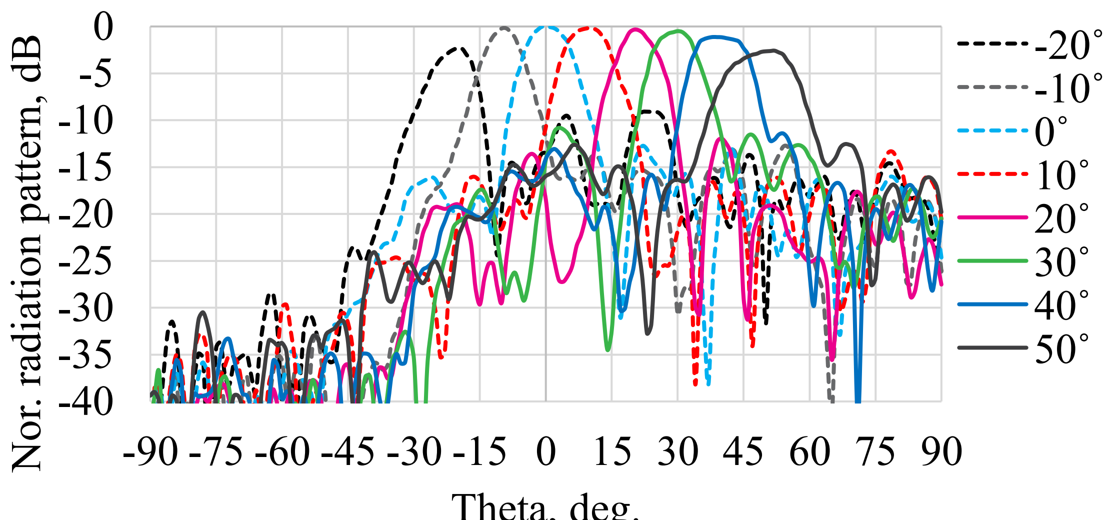




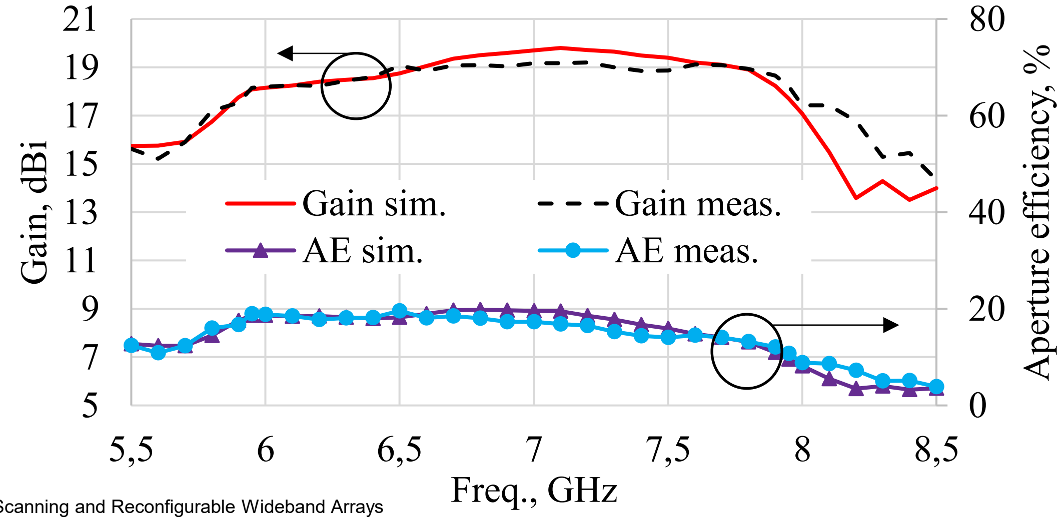
Array measurement results



Horizontal plane (E-plane) at 6.75 GHz



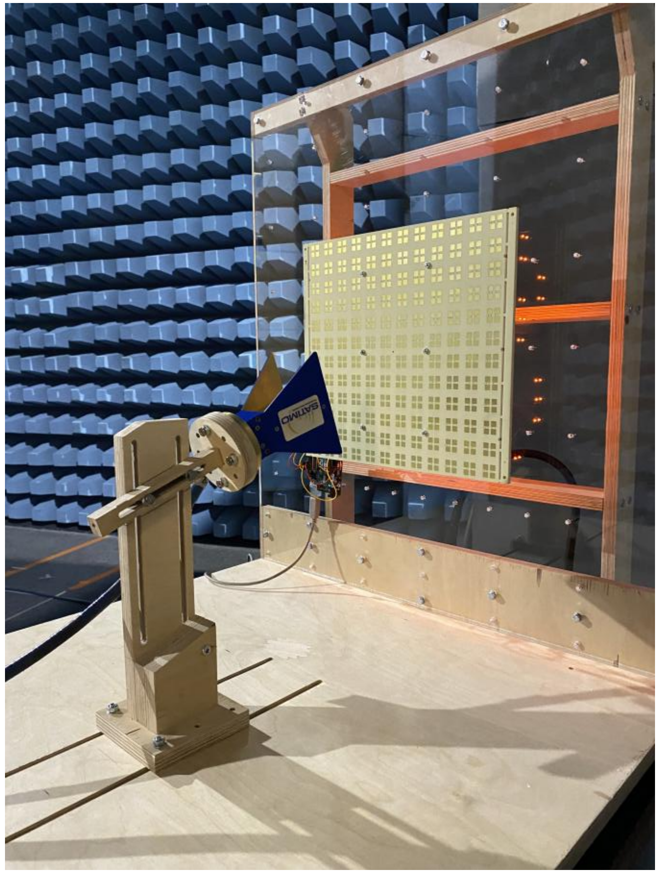
Vertical plane (H-plane) at 6.75 GHz



- Max gain: 19.2 dBi at 7.2 GHz.
- 1dB gain BW: 5.95 – 7.97 GHz (29%).
- 3dB gain BW: 5.75 – 8.26 GHz (35.8%).
- Max aperture efficiency 23.5% at 6.5 GHz, scan 20 deg. in the H- plane (YOZ).
- Scan ±50° with scan loss ≤ 3 dB from 6 – 7.5 GHz.

Summary: Reconfigurable Reflectarray

- Reconfiguration: 1-bit PIN diode switching (0° / 180° phase)
- Polarization: Single Linear Polarization (LP)
- Operating Band: 5.75 – 8.26 GHz
  → Covers 6.4 – 7.1 GHz (proposed band for 6G)
- Gain Bandwidths:
  - 1-dB BW: 29%
  - 3-dB BW: 35.8%
- Aperture Efficiency: 24%
- Beam Scanning: ±50° with scan loss of ≤ 3 dB



Q. D. Nguyen, N. Takanen, M. Abdullah, D. T. Phan and P. J. Soh, "A 1-Bit Reconfigurable Reflectarray with Improved Gain Bandwidth for 6G Applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 25, no. 1, pp. 114-118, Jan. 2026, doi: 10.1109/LAWP.2025.3619055.

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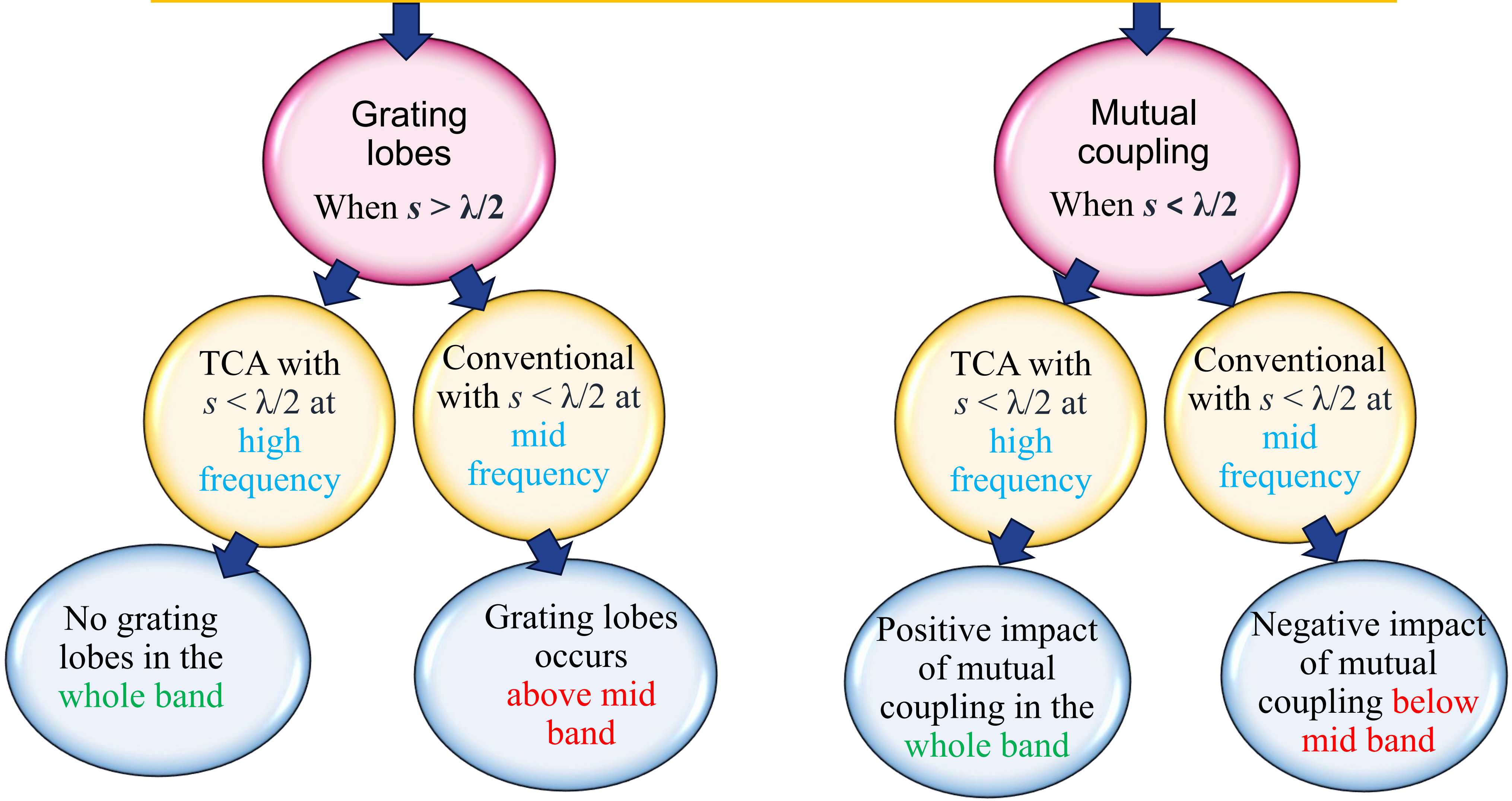
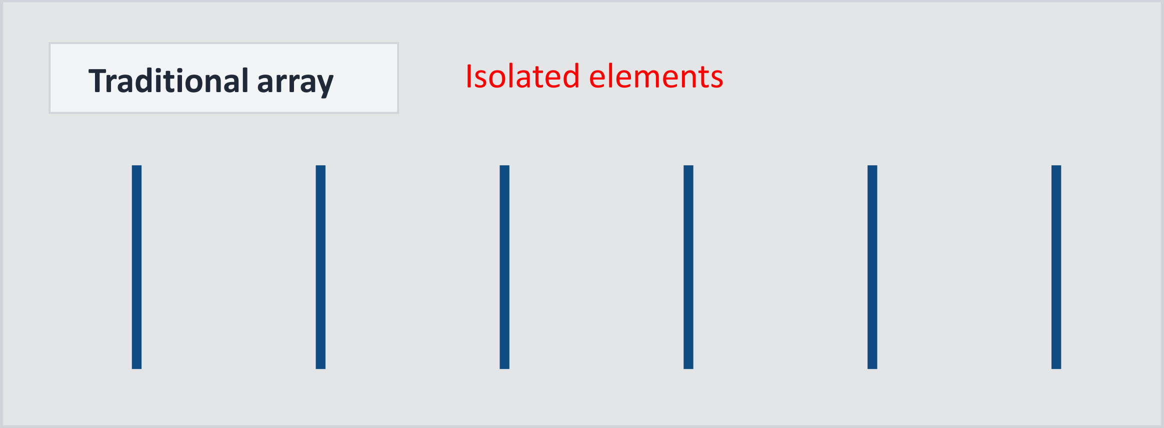
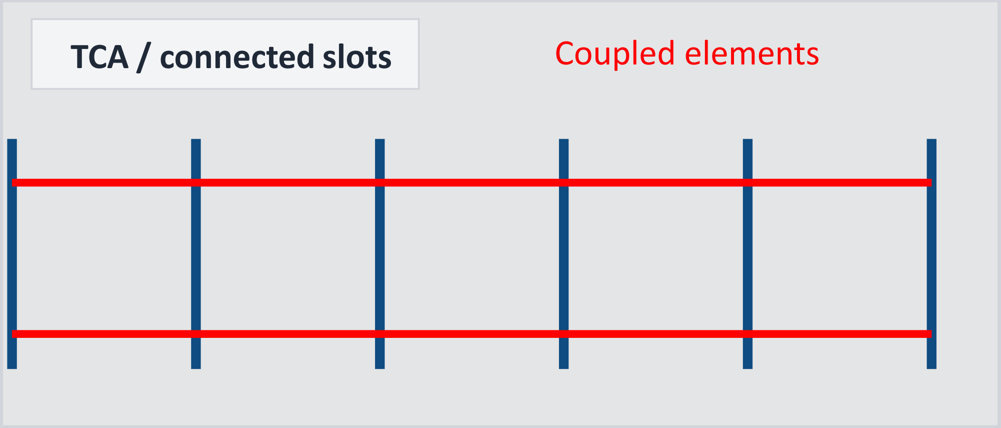
Motivation for Tightly Coupled Arrays (TCA):

TCA vs conv phased array design tradeoffs



TCA Benefits and constraints





TCAs concepts

Intentional strong coupling
↓
Slow wave
↓
Wideband imp matching
↓
Wideband behaviour

Benefits of TCAs

- **Ultra-wideband** – Broad matching via coupling
- **Wide-angle scan** – Improved scan impedance
- **Single-layer WAIM** – Simpler scan match
- **Fewer grating lobes** – Compact s < λ/2 at high-f
- **Controlled coupling** – Supports broadband behavior

TCAs Constraints

- Minimum 8×8 array size
- Finite size edge effects

Wideband Wide Scanning Phase Array

Target Specifications

- Initial target in sub-6 GHz FR1: 1.6-4.2 GHz (FBW ~90%), next is FR3 (7-15 GHz)
- Spacing between two elements= 33 mm
- Simplified manufacturing/assembly
- In terms of λ:
    - At 1.6 GHz spacing: 0.1 λ
    - At 4.2 GHz spacing: 0.46 λ

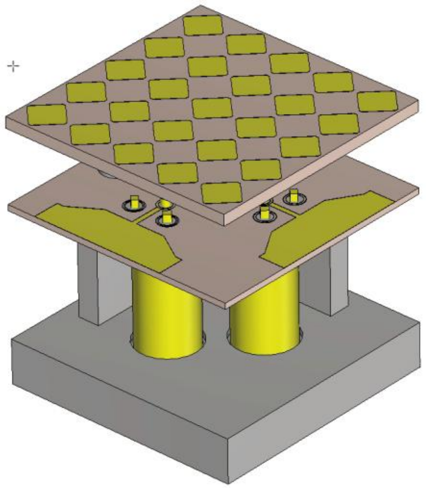


Fig. Proposed Unit cell.

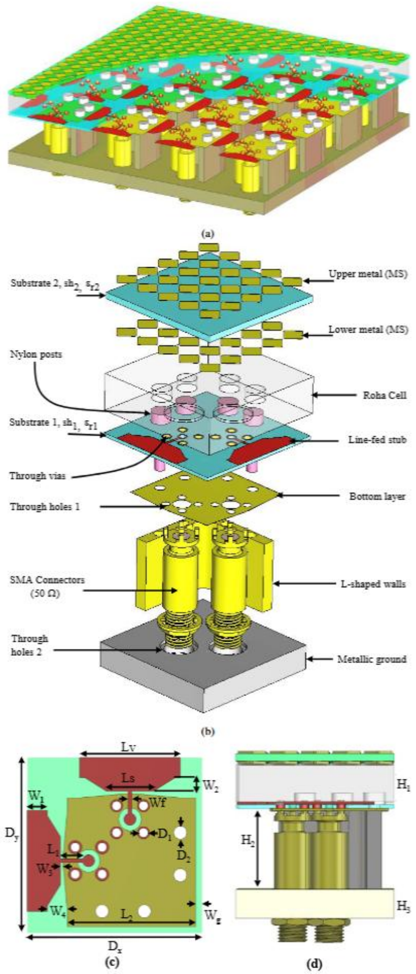


Fig. 4 x 4 subarray and exploded view of unit cell

Unit cell design: CSA

Impedance matching:

- Line-fed stub and gaps are introduced to match the unit cell
- The feedline is terminated with stub and capacitively feed the slot

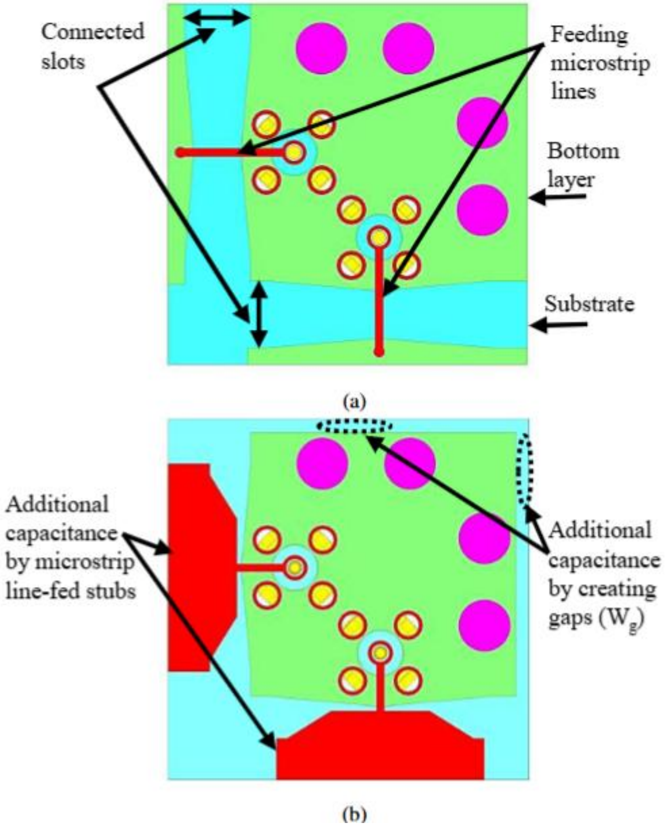


Fig. (a) General CSA unit cell. (b) Proposed CSA with both Wg and line-fed stubs

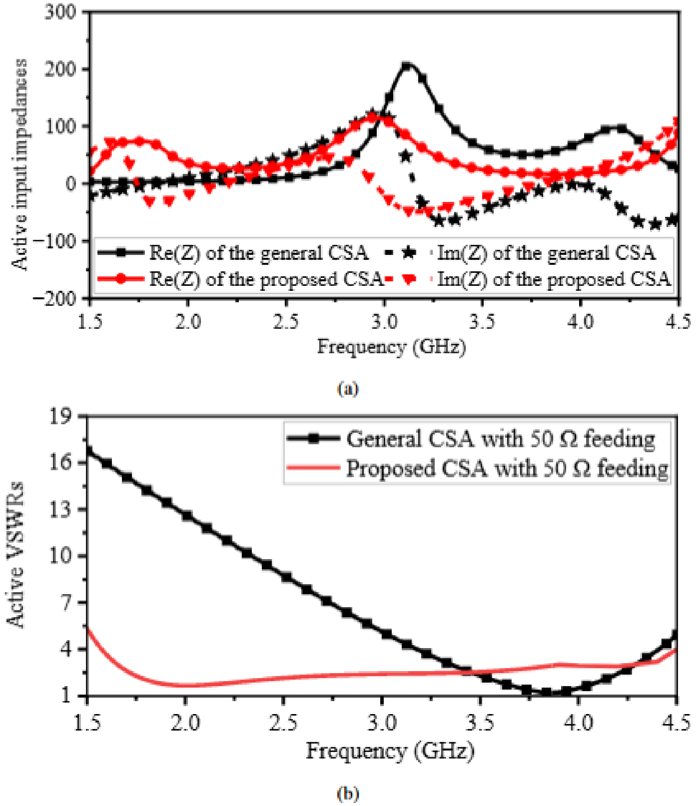


Fig. (a) Comparison of active input impedances of the general and proposed CSA. (b) Comparison of active VSWRs of all unit cell configurations.

Unit cell transition to 8x8 array

- The unit cell is simulated with periodic boundary conditions to predict infinite array
- For a finite array performance, the unit cell is converted to 8 x8 array
- The 8 x 8 array is simulated with open-add-space boundary conditions and later on prototyped.

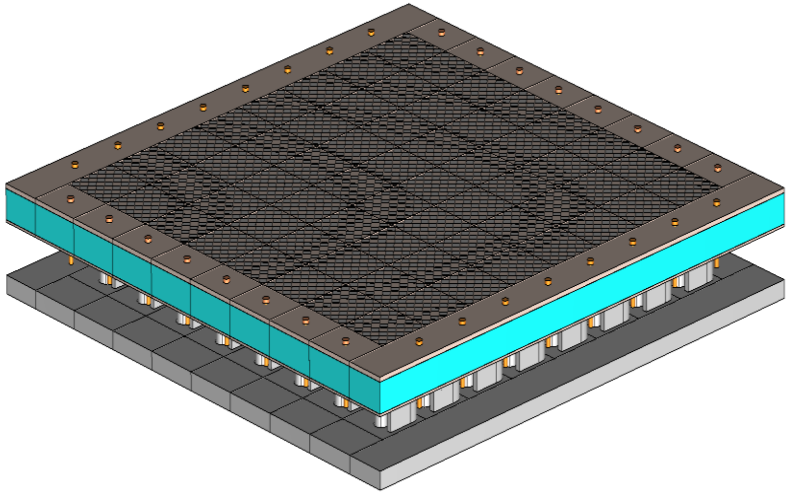


Fig. Simulated 8 × 8 elements finite array.

S-parameter results (sim vs meas)

Scanning in E-plane: 65^0

Scanning in H-plane: 55^0

Scanning in D-plane: 65^0

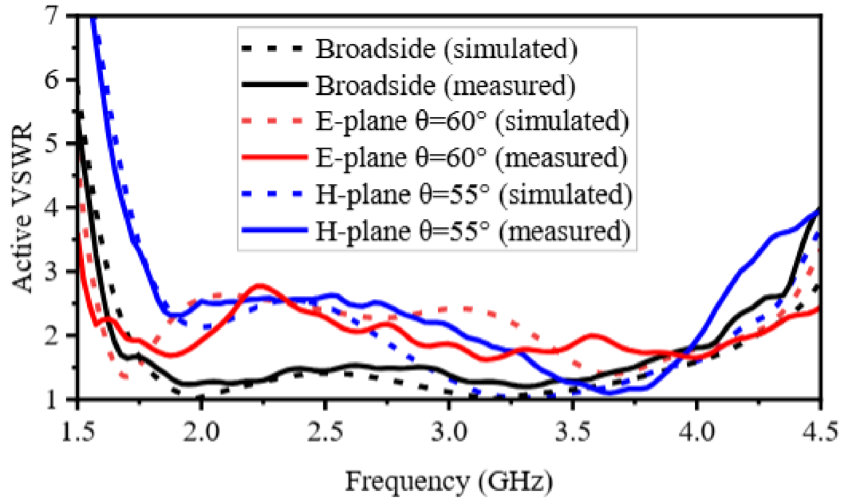
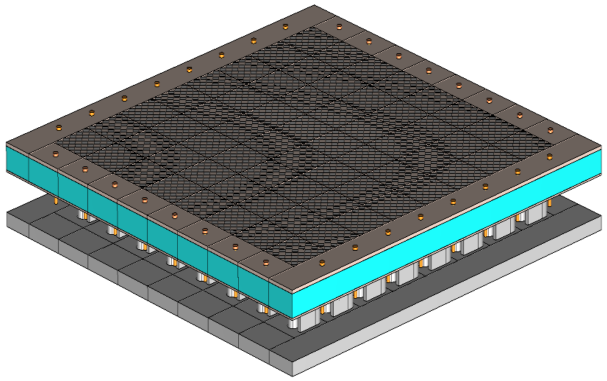


Fig. Comparison of the simulated and measured VSWRs of the central element (5, 5) of the proposed 8 × 8 array.



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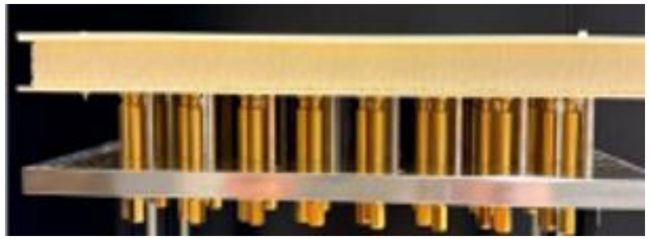


Fig. Prototyped 8 × 8 elements finite array.

Bandwidth Enhancement Method

– Unwanted Common Mode Resonance (CMR) suppression

- L-shaped metallic walls for 2 functions:

1. Shift the CMR out of the operating band of interest in the dual polarized antenna
2. Provide robust mechanical support to the radiators on the upper layers

- Air between the slots and the ground plane

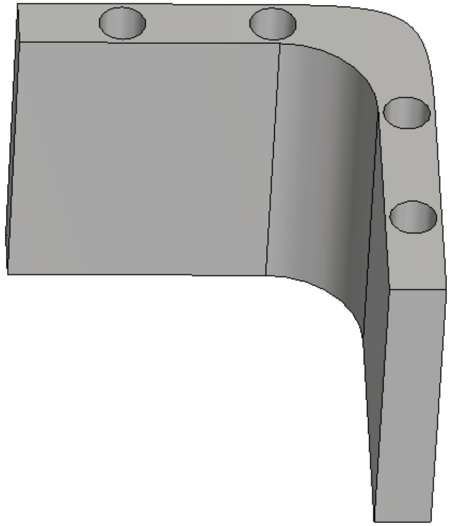


Fig. L-shaped Metallic Wall for mitigation of CMR

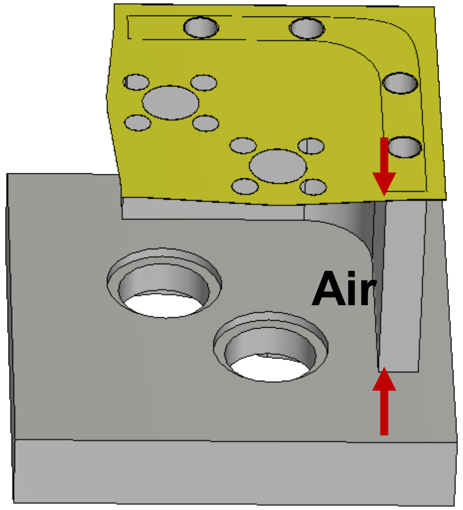


Fig. Proposed unit cell with air in between the slot and the ground plane

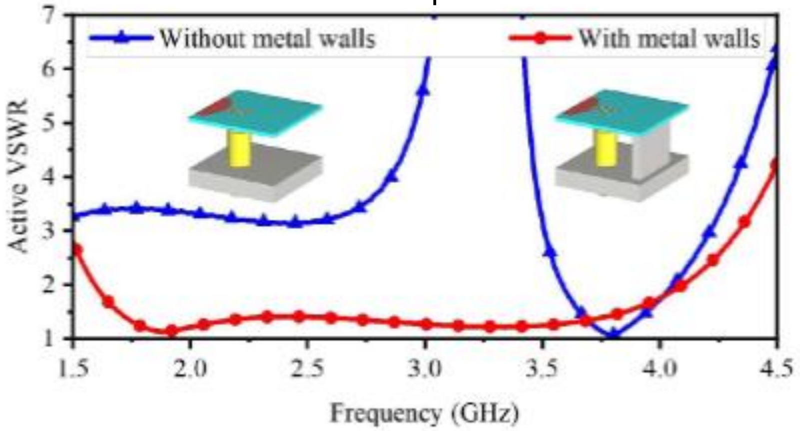


Fig. Active VSWR with and without metallic wall during scanning in the H-plane

Manufacturing Simplification

– Feeding method

- SMA connectors have been used to feed the dual-polarized antenna to simplify fabrication

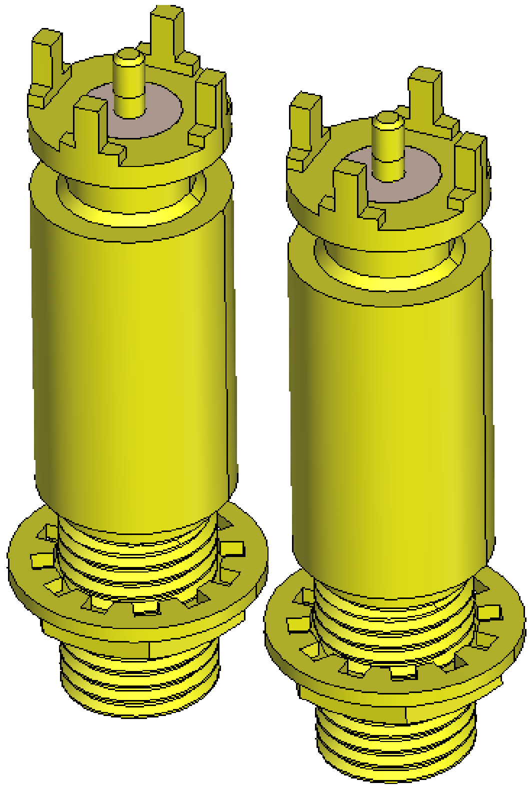


Fig. SMA connectors for dual polarization

Wide-angle Scan Enhancement

– **Wide Angle Impedance Matching (WAIM) Layer**

- A WAIM layer consisting of diamond-shaped patches have been used to increase scanning performance

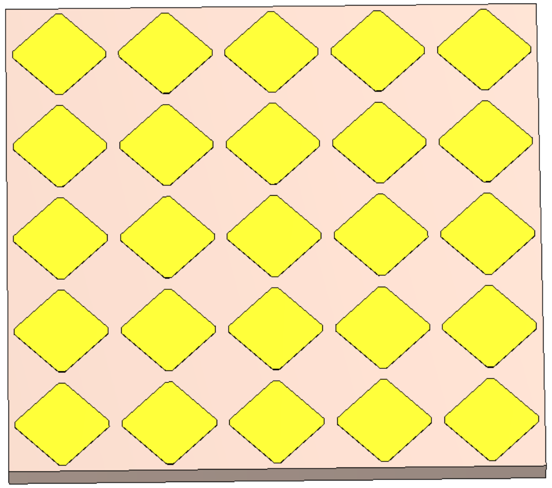


Fig. Proposed MS-WAIM for wide angle scanning

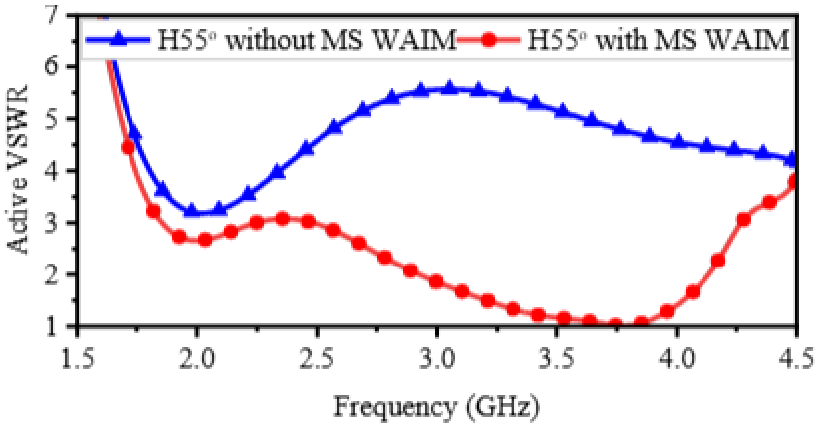
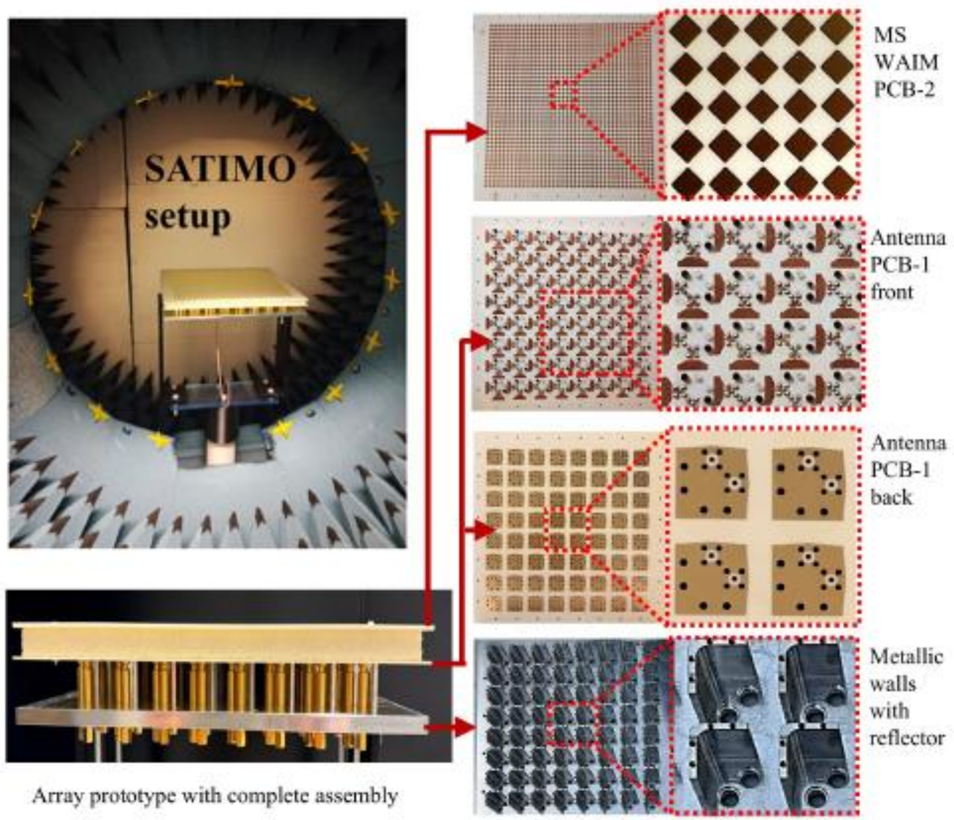
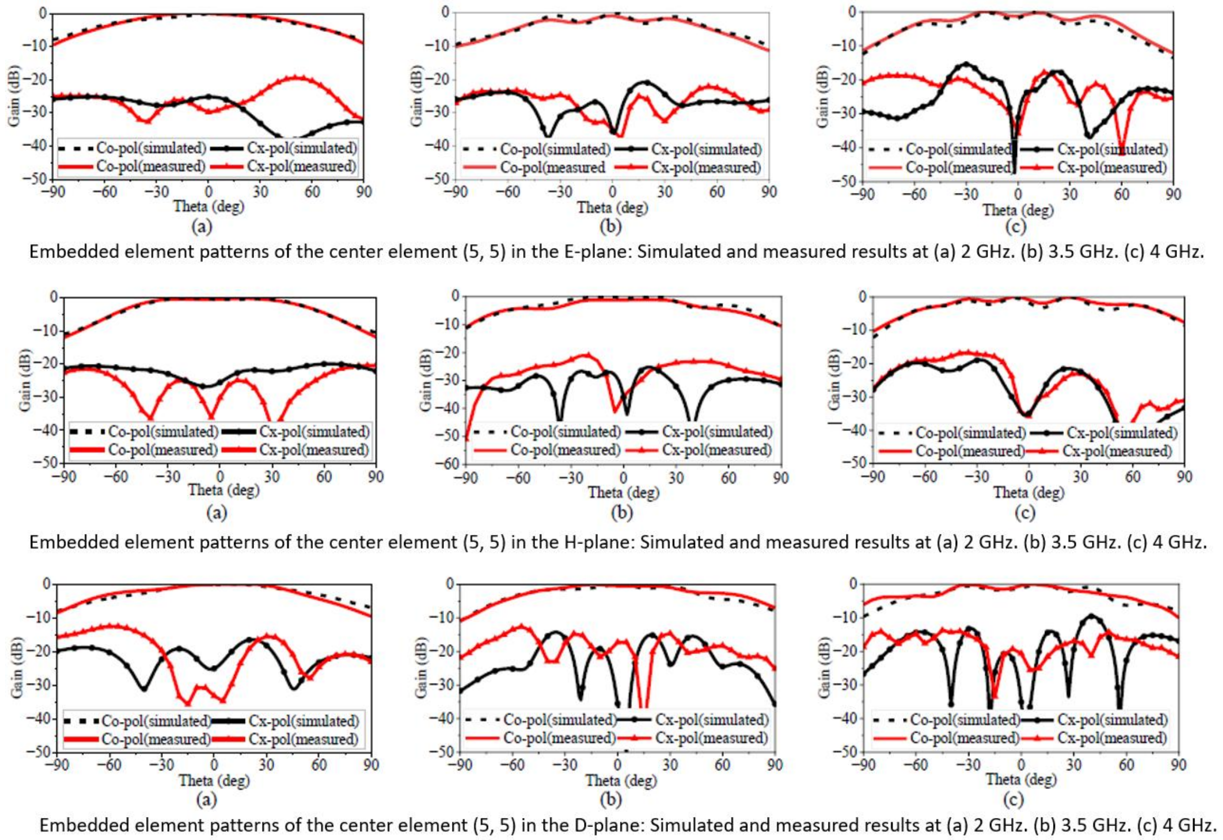


Fig. Active VSWR with and without MS-WAIM

8 x 8 array prototype and embedded element patterns

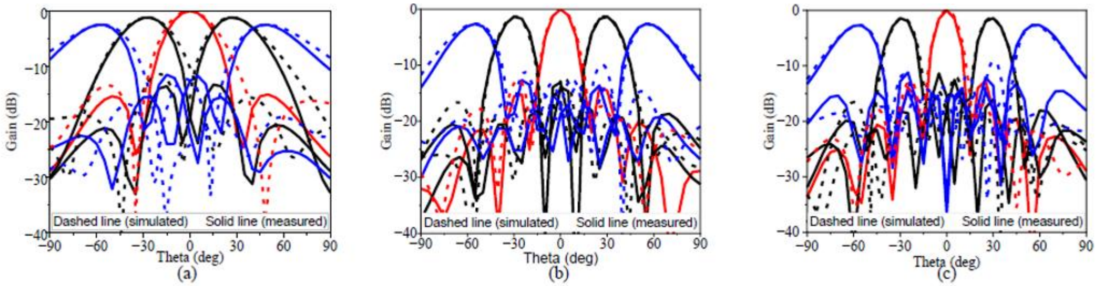


Array prototype

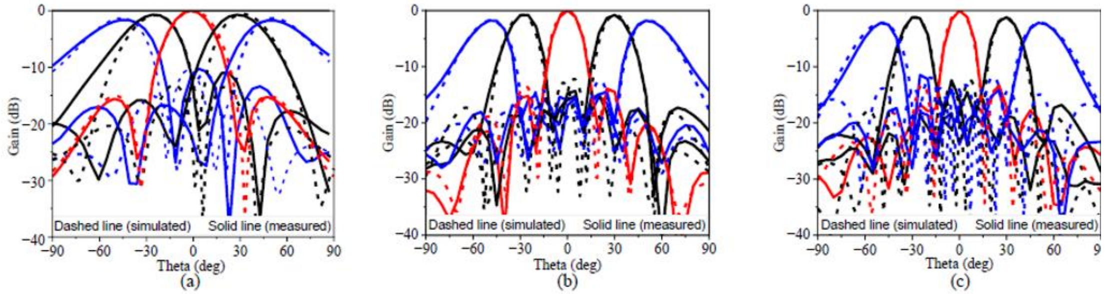


Embedded central element patterns at different planes.

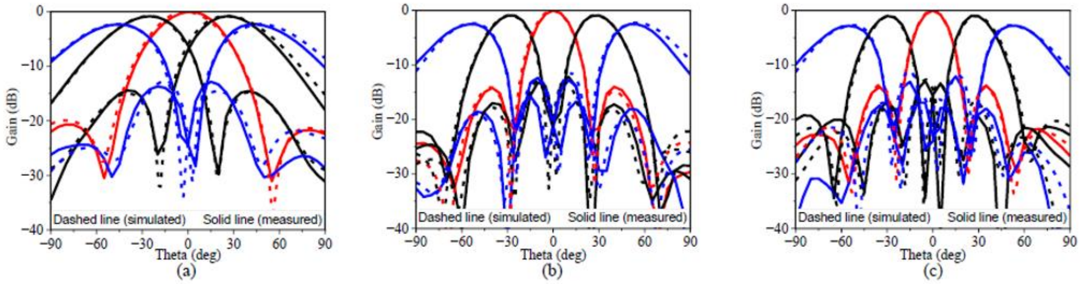
Scanning Patterns and Realized gain



Scanning patterns in the E-plane: simulated and measured results at (a) 2 GHz. (b) 3.5 GHz. (c) 4 GHz.

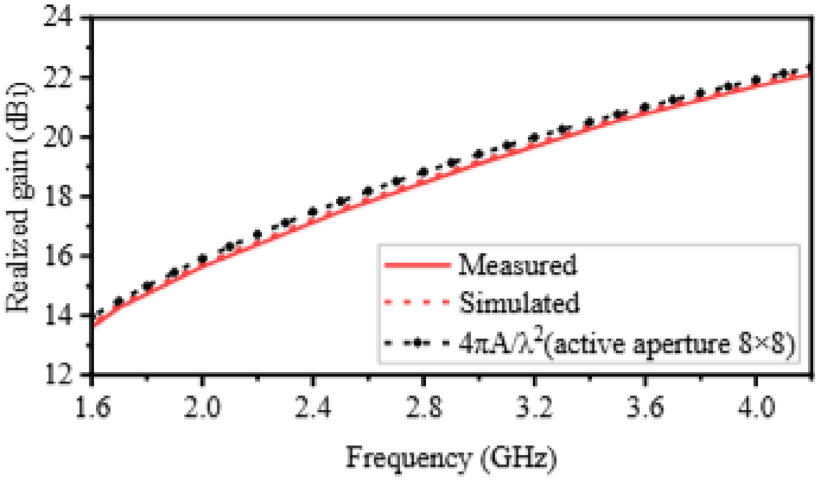


Scanning patterns in the H-plane: simulated and measured results at (a) 2 GHz. (b) 3.5 GHz. (c) 4 GHz.



Scanning patterns in the D-plane: simulated and measured results of the 4 × 8 subarray at (a) 2 GHz. (b) 3.5 GHz. (c) 4 GHz.

Scanning patterns in all planes.



Comparison of the simulated and measured realized gains

Summary: Wide Angle Scanning Array

- Planar dual-pol. connected slot array with wideband, wide-angle scanning
- Capacitive coupling + stubs to broaden bandwidth
- Standard SMA feed, no balun needed
- L-shaped walls suppress common-mode resonance and lower cost/complexity
- Single-layer MS-WAIM improves scanning, maintaining low profile
- Measured 8×8: 1.6–4.2 GHz, up to ±65° scan, VSWR < 3
- Practical low-complexity solution for potential sub-6 GHz 5G base stations

R. Ullah, J. Chen, S. J. Chin, M. E. Leinonen, A. Pärssinen and P. J. Soh, "Design of a Wideband Wide-Angle Scanning Connected Slot Array Antenna for 5G-NR FR1 Band," in *IEEE Transactions on Antennas and Propagation*, vol. 73, no. 12, pp. 9748-9762, Dec. 2025, doi: 10.1109/TAP.2025.3613554.

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Summary and Future/Ongoing Work

- Reflectarray with 2-bit tunability – increased beam versatility and aperture efficiency
- Multifunctional reflectarrays, with reflective beamsteering and absorption feature
- Wide scanning wideband phased array in FR3 (6-15 GHz)

Acknowledgements

– Doctoral researchers for the specific topics:

  - Quoc Duy Nguyen (wideband reflectarray)
  - Raza Ullah (wideband phase array)

– Funders for the research:

  - Business Finland (RF-ECO3)
  - US Office of Naval Research (LoREMA)
  - Nokia Donation (INTEGRATE)
  - Research Council of Finland (LiBERATE)

Thank you for your attention

Questions / comments?

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