Fully-Addressable Varactor-Based Reflecting Metasurface with Dual-Linear Polarisation for Low Power RISs

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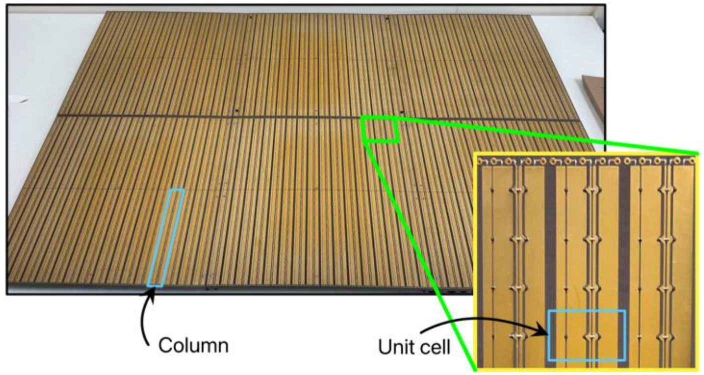
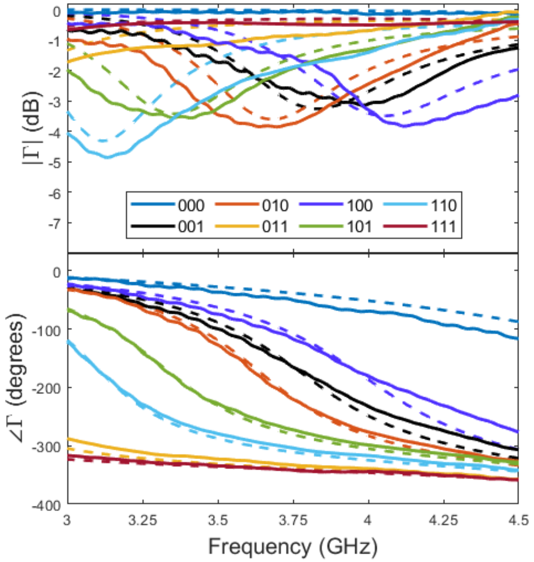
Reconfigurable intelligent surfaces at University of Glasgow

Prototyping and field trials

Small team (currently 2 people)

RIS-enabled wireless communications and sensing





nature Light Science & Applications

Usman, Rains, et al.DOI: [10.1038/s41377-022-00906-5](https://doi.org/10.1038/s41377-022-00906-5)

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION

Rains, Kazim, et al. DOI: [10.1109/TAP.2022.3216555](https://doi.org/10.1109/TAP.2022.3216555)

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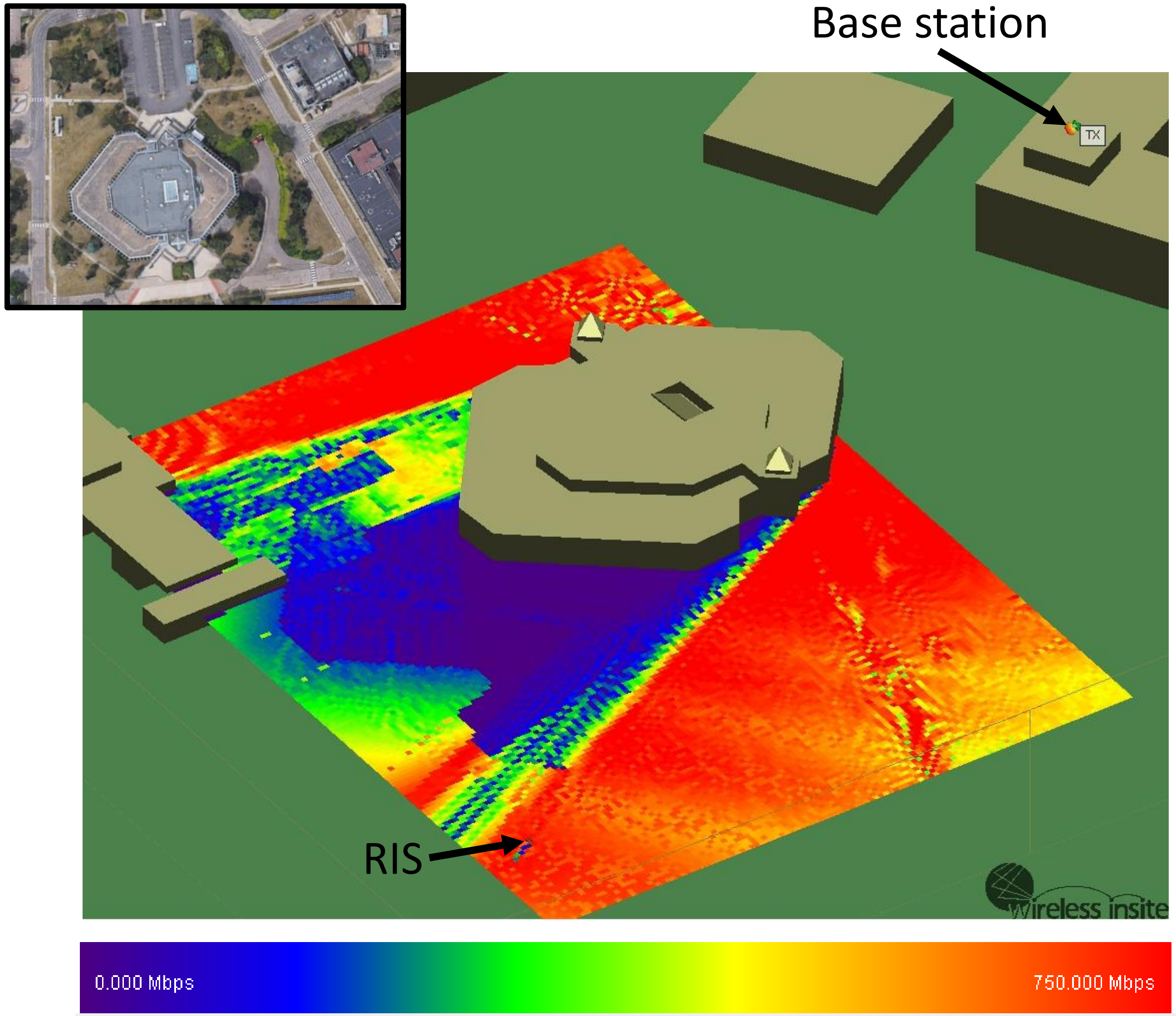
Reconfigurable intelligent surfaces for wireless coverage enhancement

Adoption of RIS within existing and soon-to-be deployed wireless networks

Can extend 5GNR sub-6 GHz coverage to blockage regions

LoS-ish performance behind occlusions

Still lacking extensive outdoor field trials



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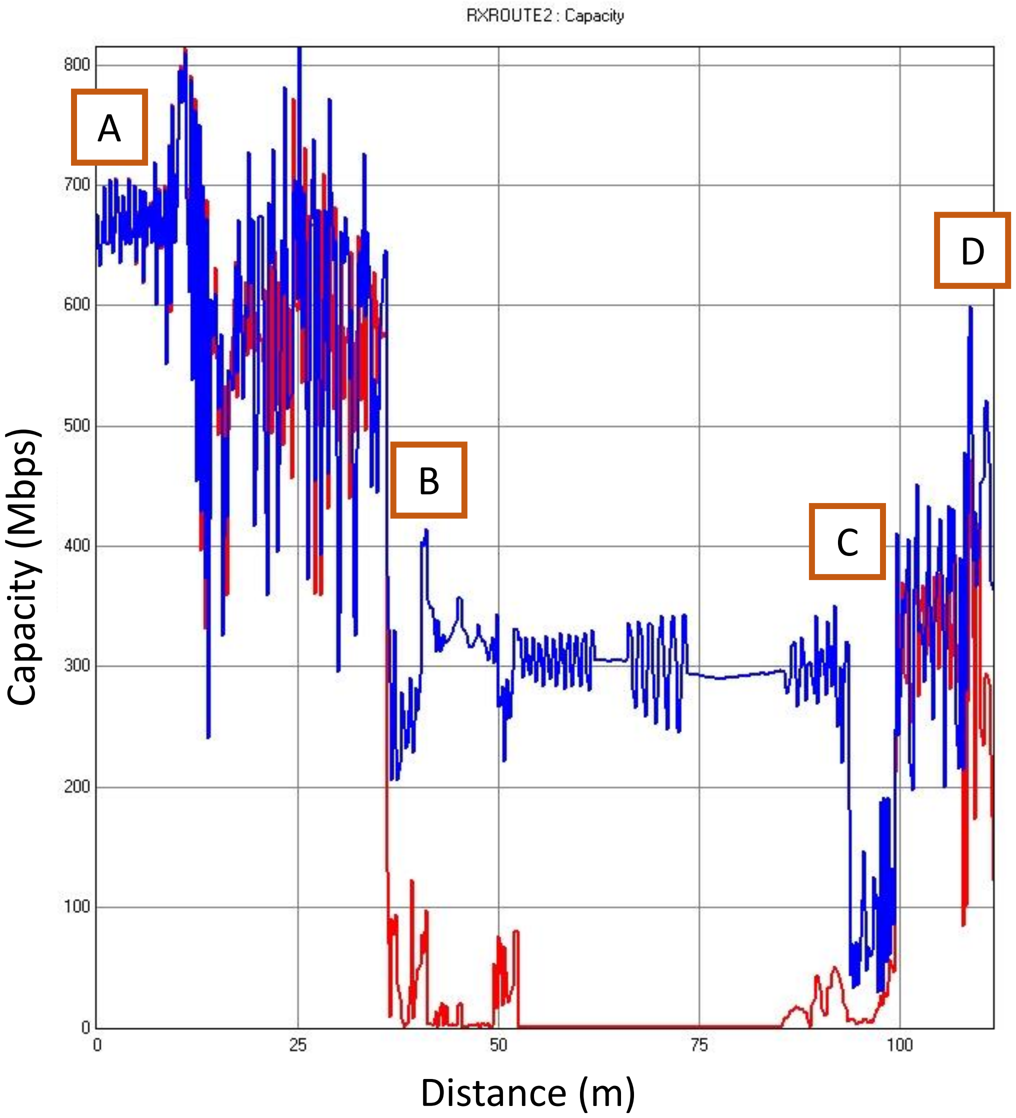
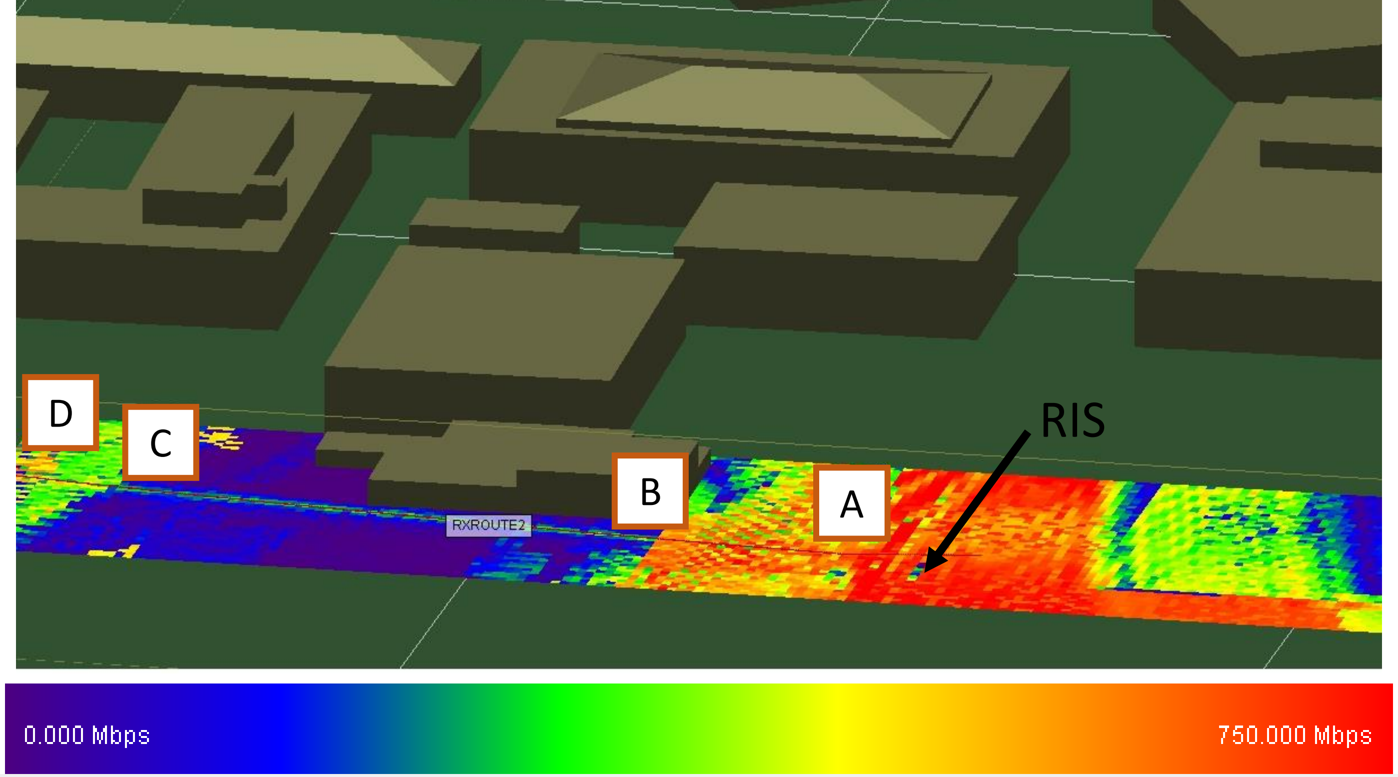
Reconfigurable intelligent surfaces for wireless coverage enhancement





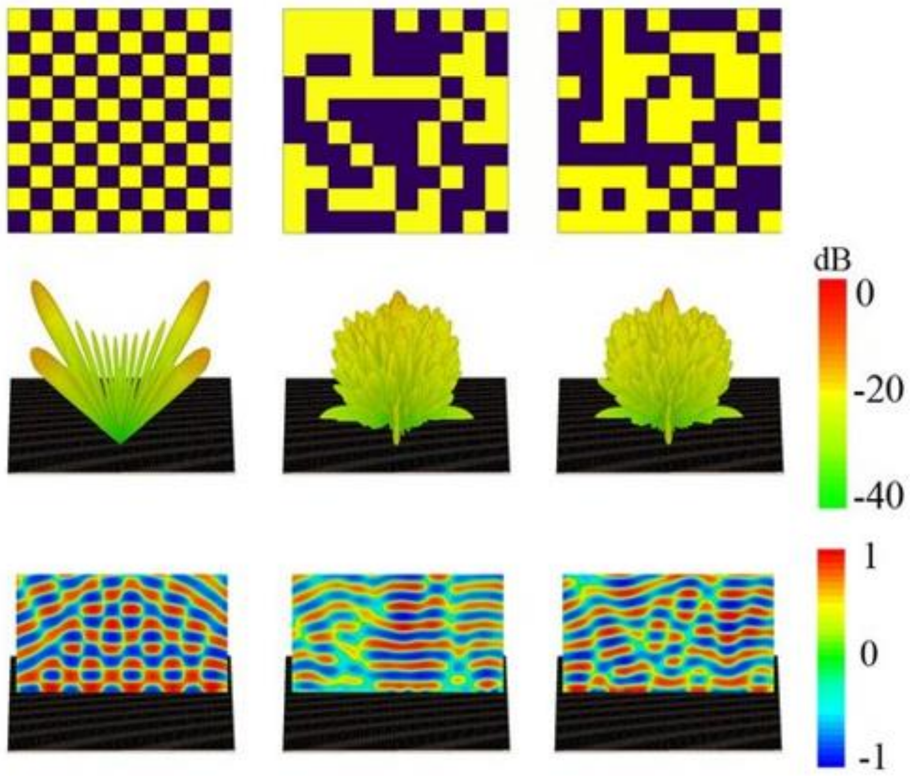
Digital metasurfaces

By spatially modulating the sheet impedance profile of a metasurface, we can couple incident waves into desired spatial harmonics

Ideally we want access to a continuous range of impedance values

Complexity is large for continuous tuning, especially if we desire full polarisation and azimuth/elevation control

Can utilise discrete sheet impedance steps to lower complexity at the expense of lower efficiency of coupling between spatial harmonics



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Design goals

3.2 – 3.8 GHz operating band

>100 MHz instantaneous bandwidth

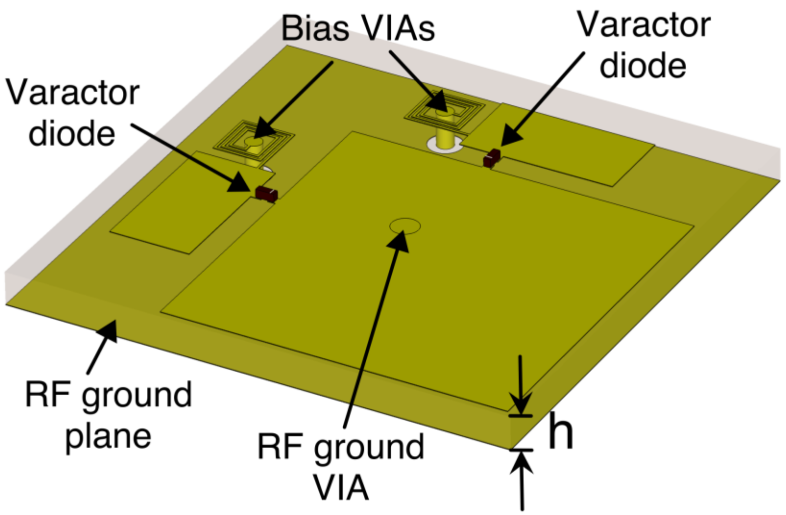
Band-tunable, 1-bit, dual-polarisation

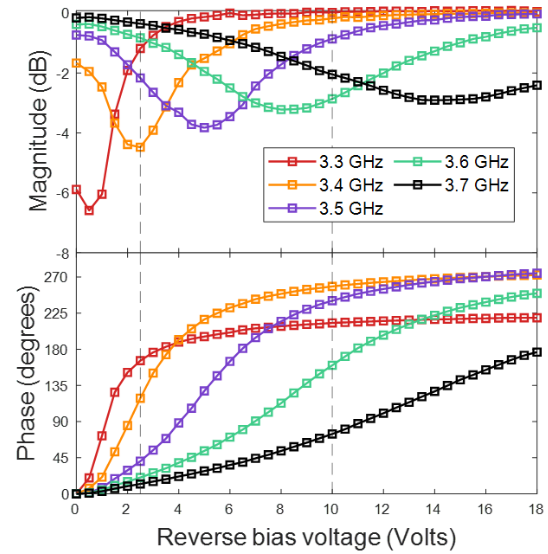
Azimuth and elevation beam steering

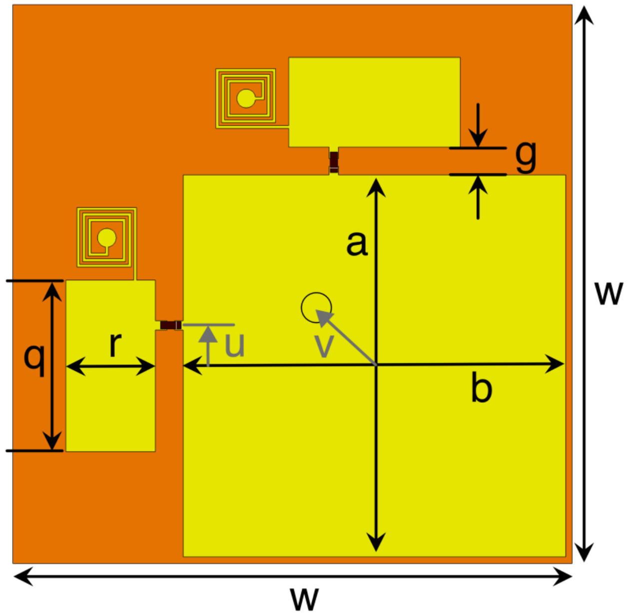
Scalable design

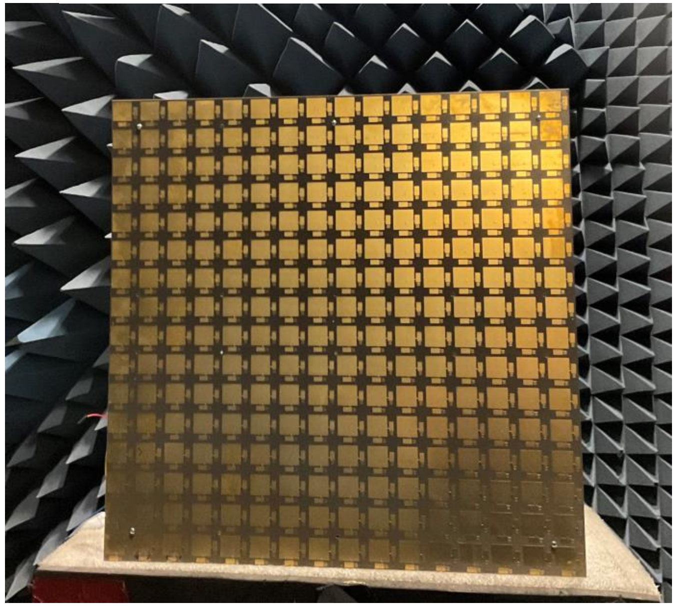
Minimal number of components

<100 mW per 16 x 16 tile





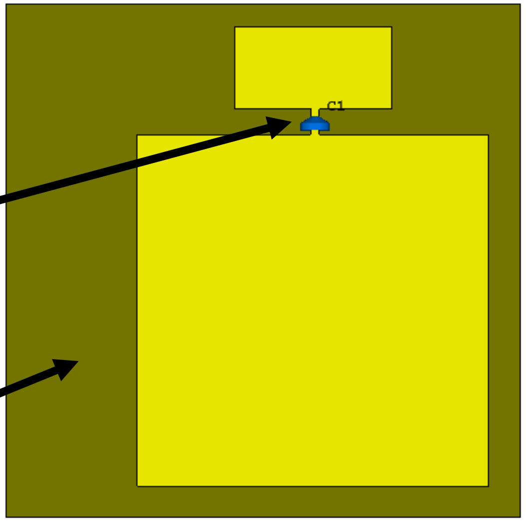


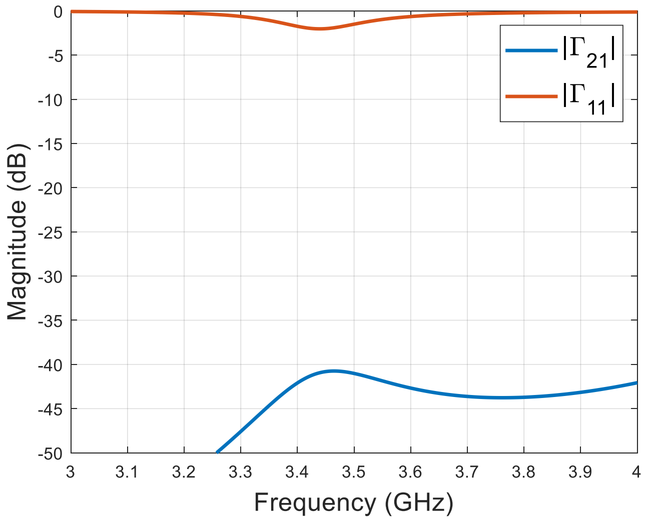


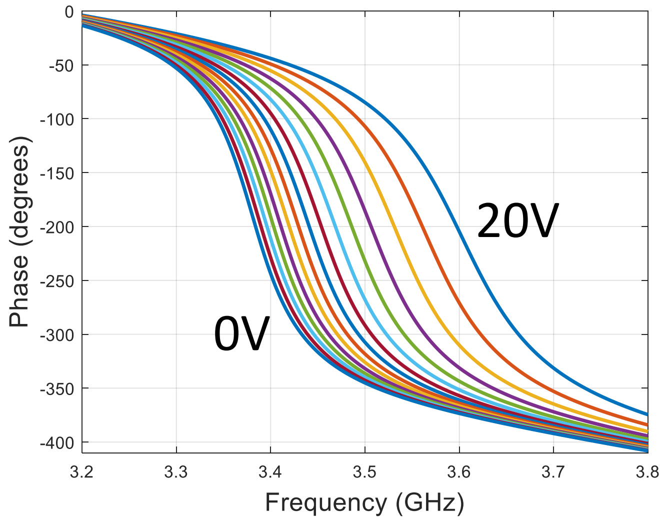
Unit cell design evolution

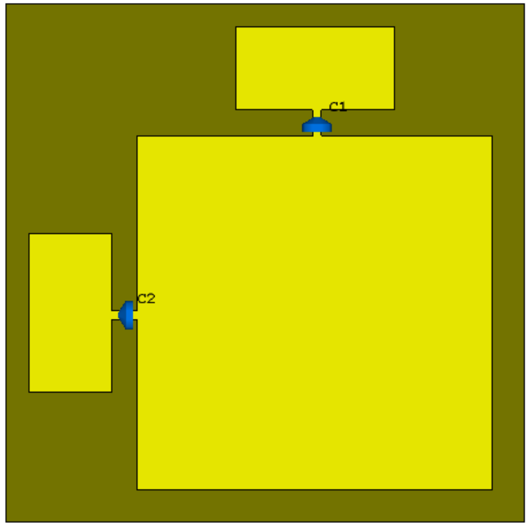
Skyworks SMV1408 varactor diode

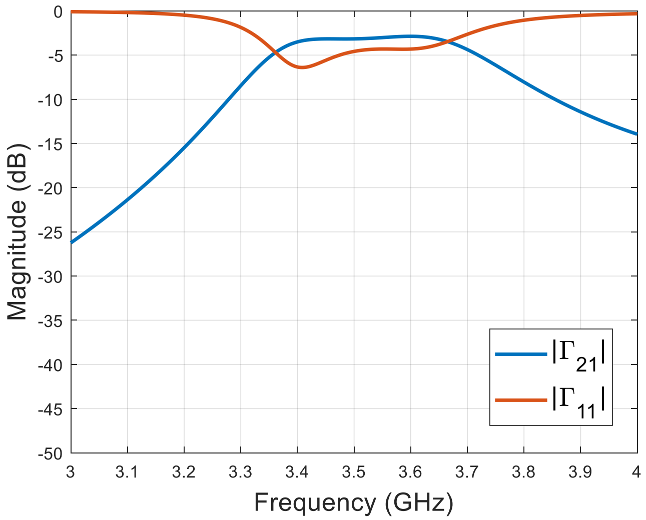
F4BM220 subtrate with ground plane

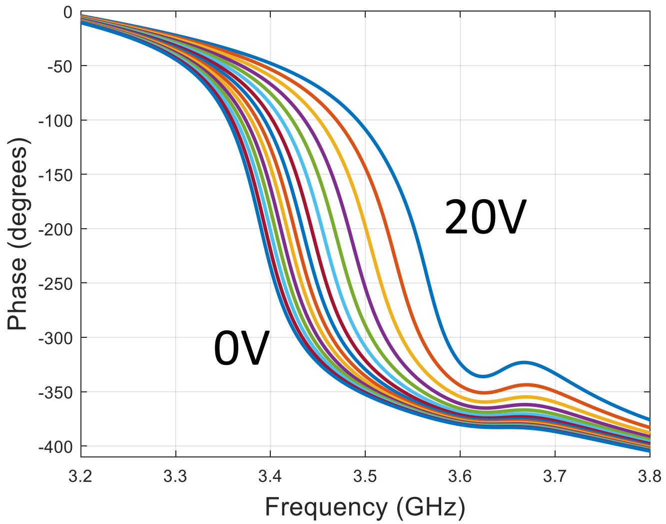












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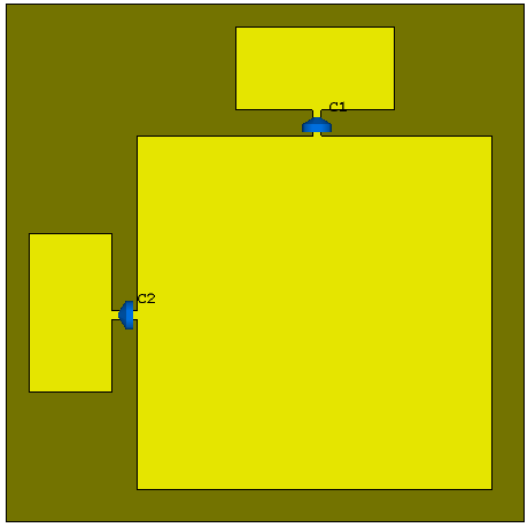
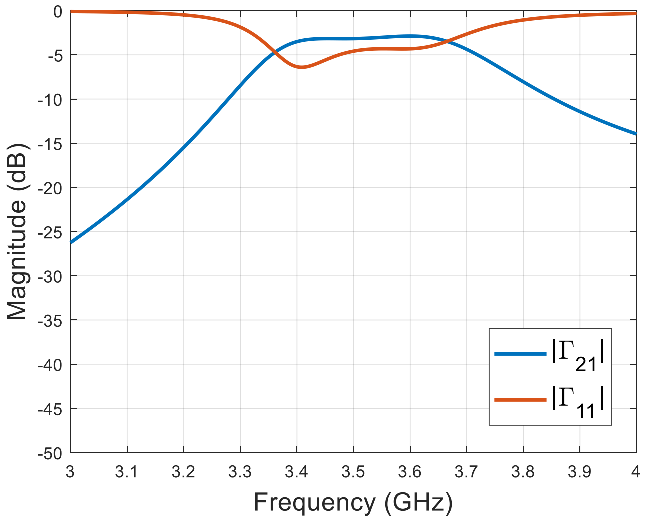
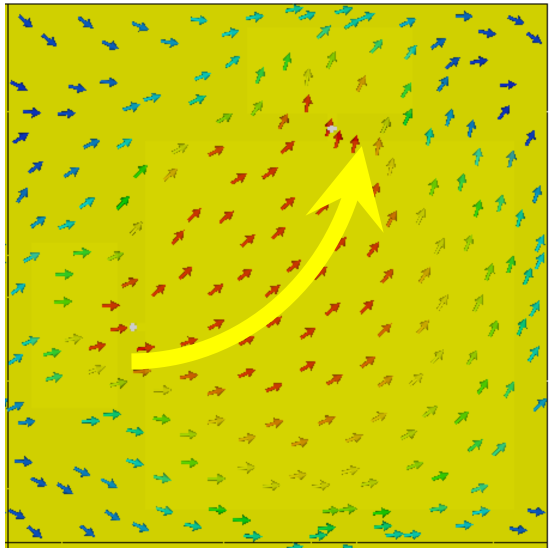
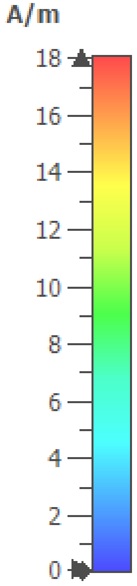
Current distribution for offset varactors

No offset

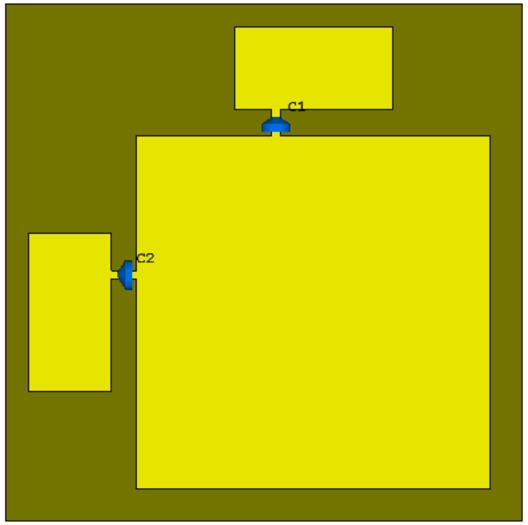


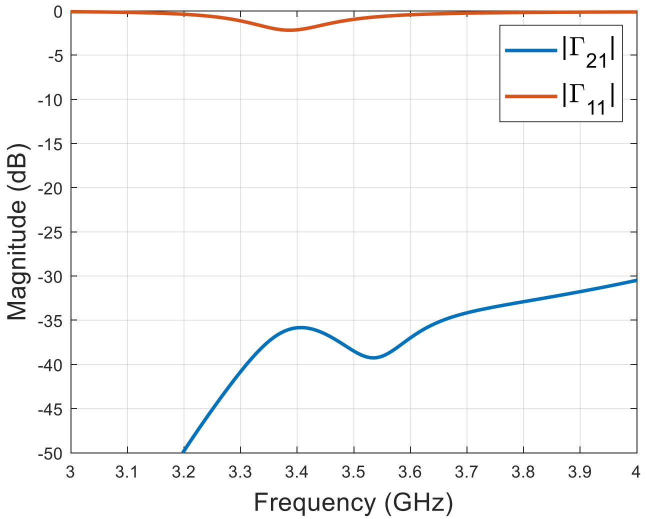


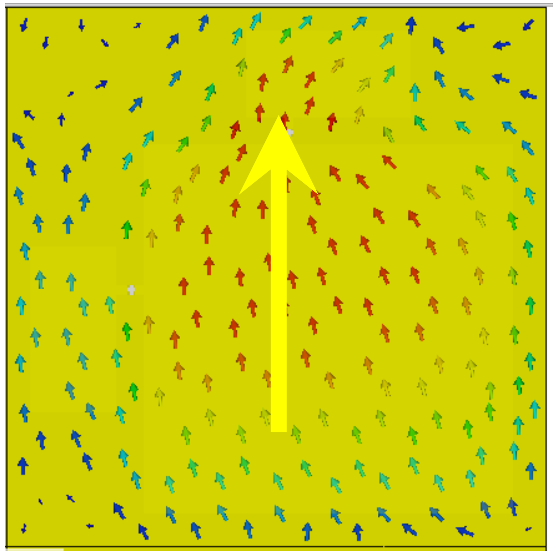




Offset







Fully-Addressable Varactor-Based Reflecting Metasurface with Dual-Linear Polarisation for Low Power RISs

Optimisation procedure

$$\begin{bmatrix} S_{L11} & S_{L12} \\ S_{L21} & S_{L22} \end{bmatrix} = \boldsymbol{S_A} + \boldsymbol{S_B}\boldsymbol{\Gamma}(\boldsymbol{I} - \boldsymbol{S_D}\,\boldsymbol{\Gamma})^{-1}\boldsymbol{S_C}$$

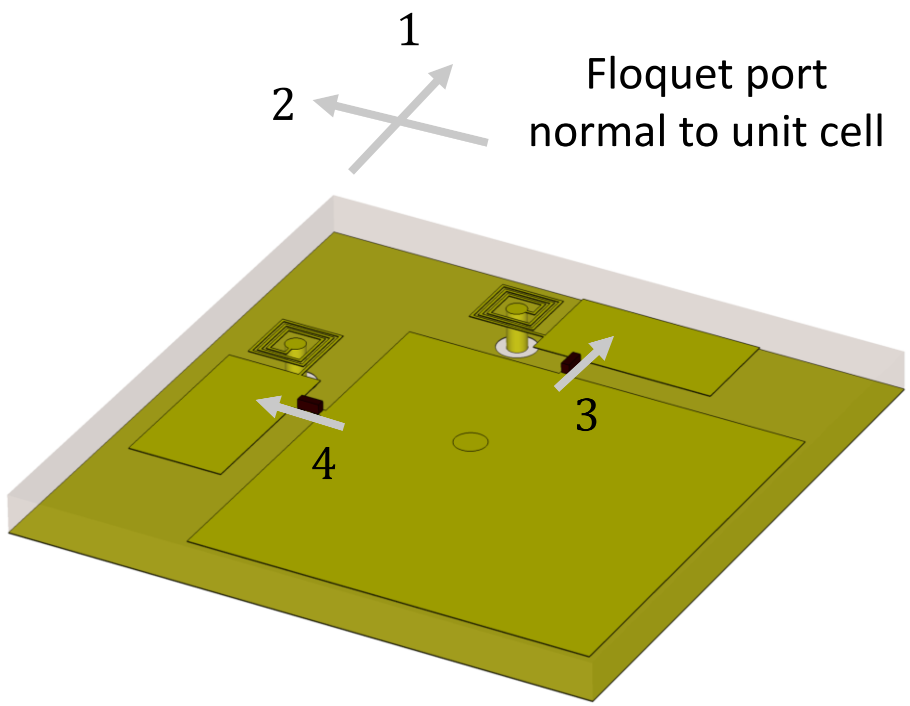
$\boldsymbol{S_A} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}$ Floquet ports (orthogonally polarised, normal incidence)

$\boldsymbol{S_B} = \begin{bmatrix} S_{13} & S_{14} \\ S_{23} & S_{24} \end{bmatrix}$ Floquet ports to varactor diode ports

$\boldsymbol{S_C} = \begin{bmatrix} S_{31} & S_{32} \\ S_{41} & S_{42} \end{bmatrix}$ Varactor diode ports to Floquet ports

$\boldsymbol{S_D} = \begin{bmatrix} S_{33} & S_{34} \\ S_{43} & S_{44} \end{bmatrix}$ Varactor diode ports to varactor diode ports

$\boldsymbol{\Gamma} = \begin{bmatrix} \Gamma_1 & 0 \\ 0 & \Gamma_2 \end{bmatrix}$ Obtained by transforming two-port network .s2p files to series impedance and calculating reflection coefficients



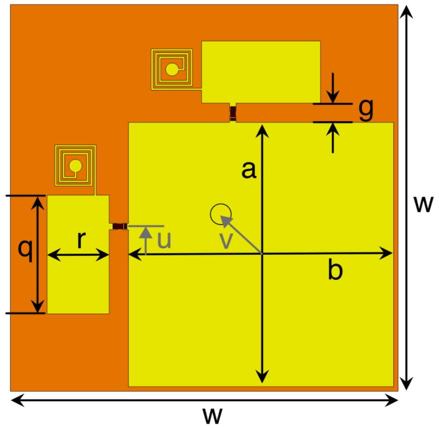
Constraints

Substrate thickness $\leq$ 2 mm

Periodicity $\leq 0.35\lambda_0$

Feasible patch geometry

Varactor voltage constraints

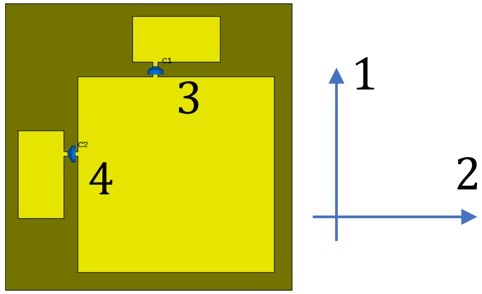


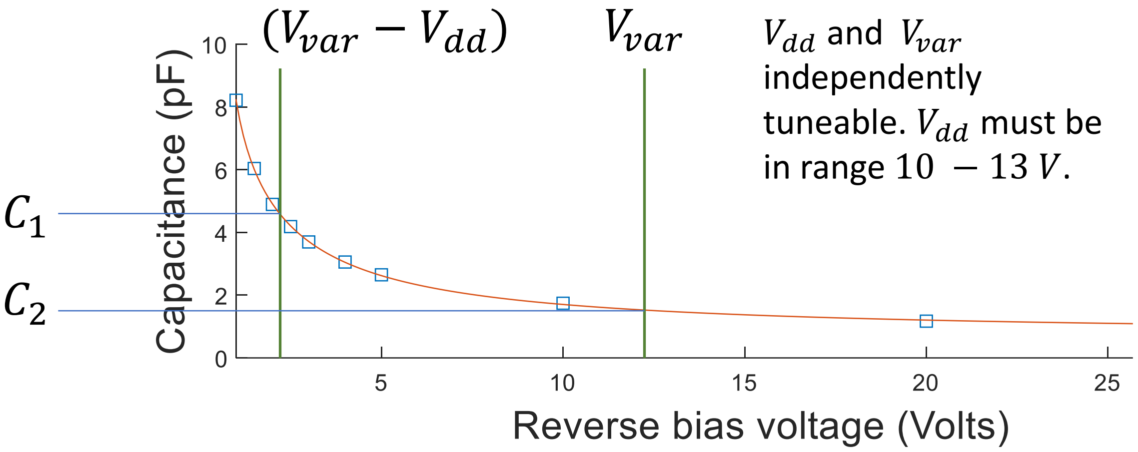
Γ_1 to Γ_2 generated from S2P files of Skyworks SMV1408 varactor diodes at 0V to 20V

Fully-Addressable Varactor-Based Reflecting Metasurface with Dual-Linear Polarisation for Low Power RISs

Optimisation procedure

Goals at 3.4, 3.5, 3.6 GHz:
Minimise reflection loss
Minimise phase error
Minimise average cross polarisation





Per particle cost derivation:

- Simulate unit cell (frequency domain solver, 3 frequency points – 3.4, 3.5, 3.6 GHz)
- Test set of capacitances and select C_1, C_2 pair with best phase error performance. Curve fitting performed on capacitance versus voltage of SMV1408:

$$C_1(V) = \beta_1 + \frac{\beta_2}{V} + \frac{\beta_3}{V^2} + \frac{\beta_4}{V^3}$$
$$C_2(V) = C_1(V + V_{dd})$$
$$V_{dd} \approx 10\ V$$

- Calculate cost for selected capacitance pair:

$$f_{cost} = \alpha_1 \left[1 - \overline{S_{L11,22}(C_1, C_2)}\right] + \alpha_2 \overline{S_{L21}(C_1, C_2)} + \alpha_3 \epsilon(C_1, C_2)$$

$$\epsilon(C_1, C_2) = \pi - |\phi(C_2) - \phi(C_1)|$$

$$\begin{bmatrix} S_{L11} & S_{L12} \\ S_{L21} & S_{L22} \end{bmatrix} = \boldsymbol{S_A} + \boldsymbol{S_B}\boldsymbol{\Gamma}(\boldsymbol{I} - \boldsymbol{S_D}\,\boldsymbol{\Gamma})^{-1}\boldsymbol{S_C}$$

$\boldsymbol{\Gamma}$ diagonal 2×2 matrix of reflection coefficients of shorted varactor diodes

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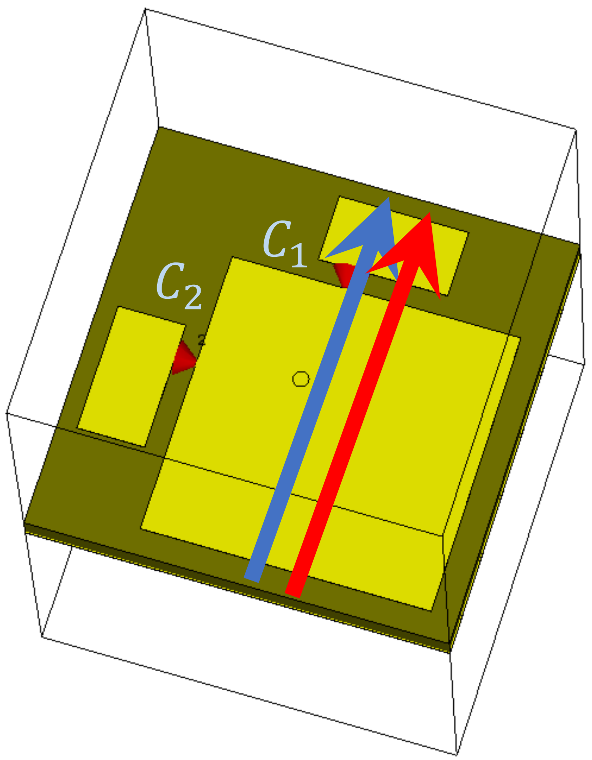
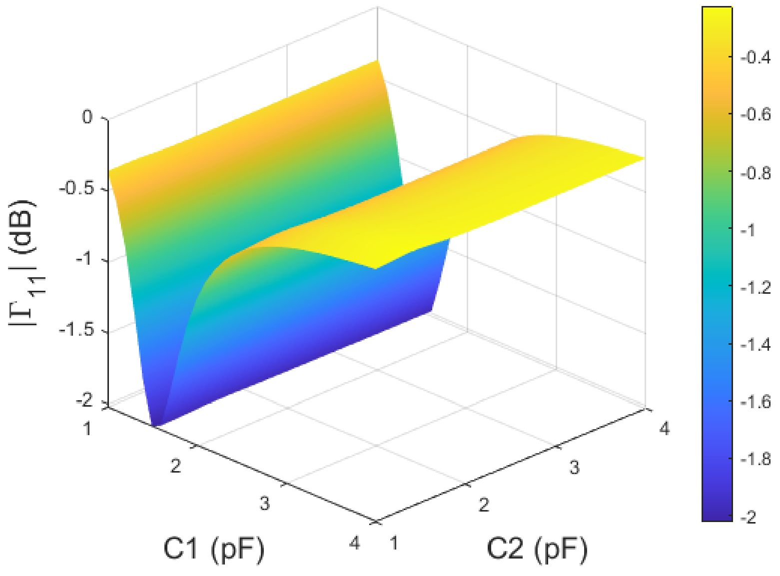
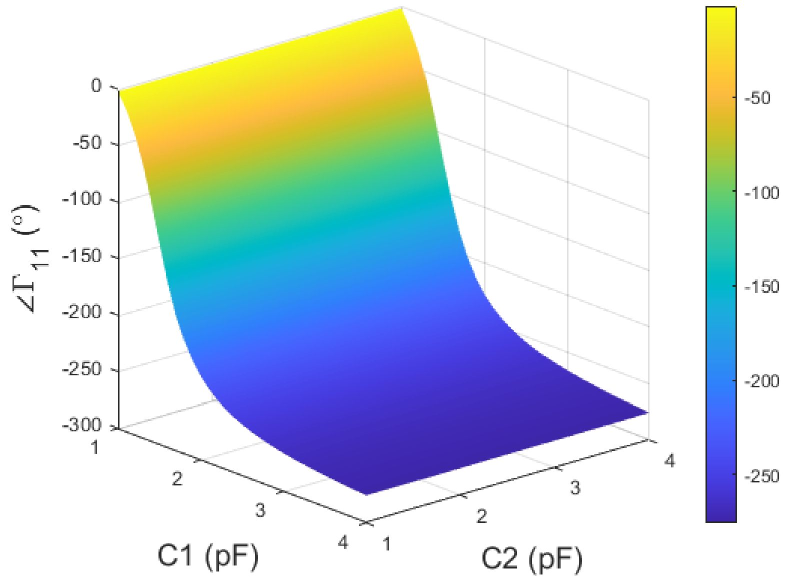
Optimisation results: co-polar magnitude and phase at 3.5 GHz





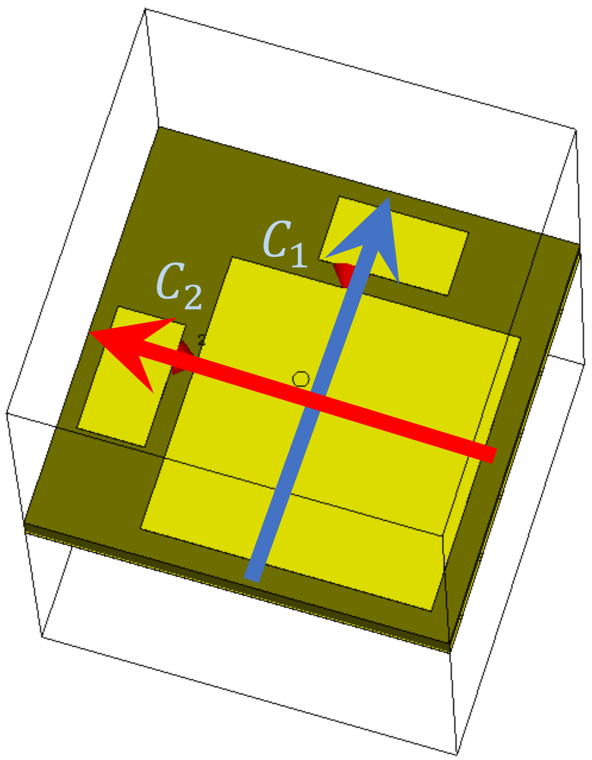
Magnitude

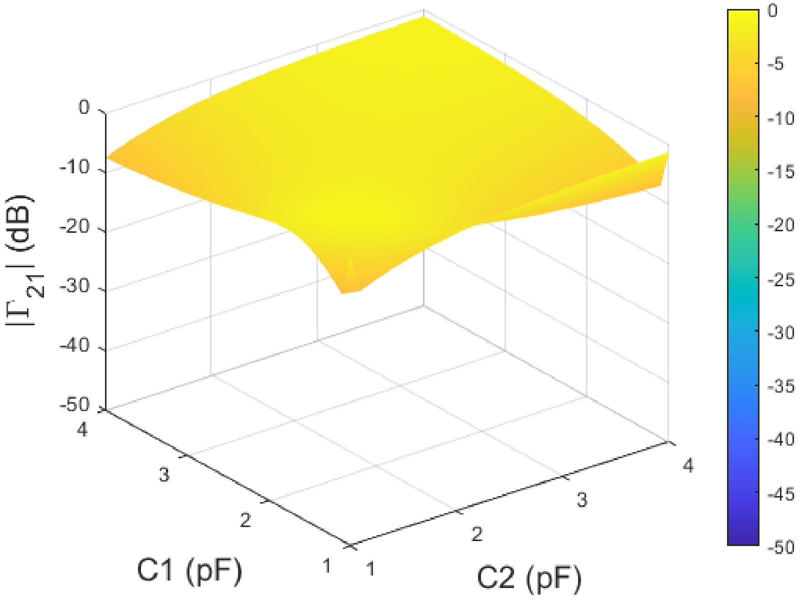


Phase

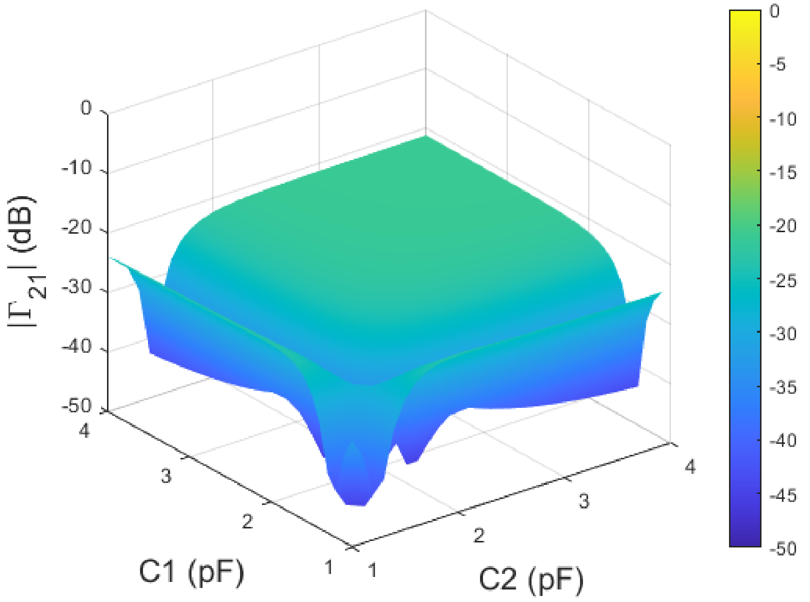
No discernible change in co-polar reflection response with variation in cross-polar varactor capacitance

Optimisation results: cross-polar magnitude at 3.5 GHz





Prior



Post

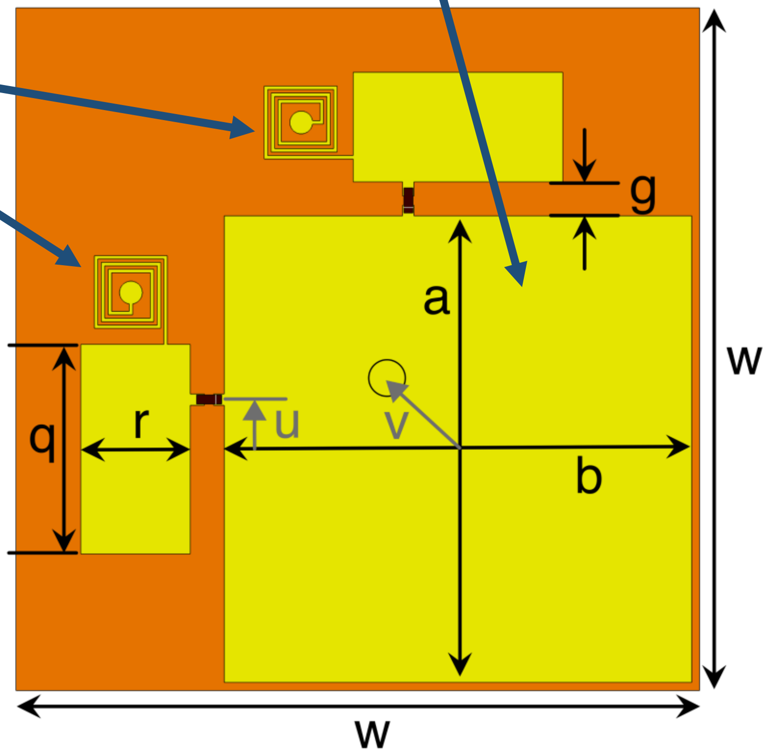
Cross-polar isolation of 30-40 dB can be achieved for subset of varactor capacitances. Minimum 21 dB.

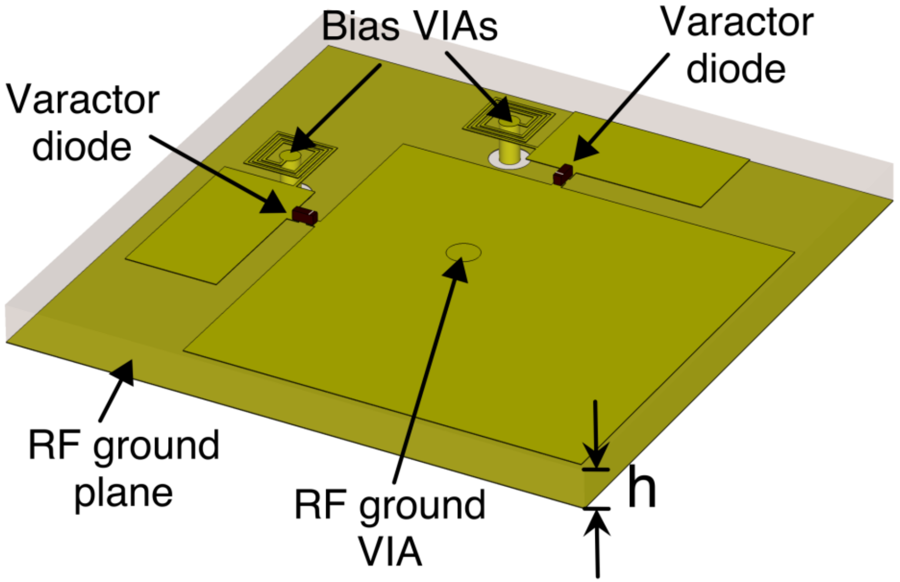
Biasing network

Parasitic patches connected to control circuit through spiral inductors

Optimised separately in Microwave Office

Second voltage applied to RF ground plane connected to square patch





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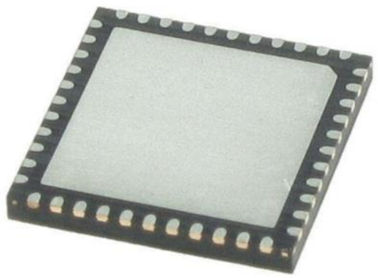
Configuration circuitry

Problem: varactors require higher voltages than conventional digital circuitry typically provides – high volume of circuitry!

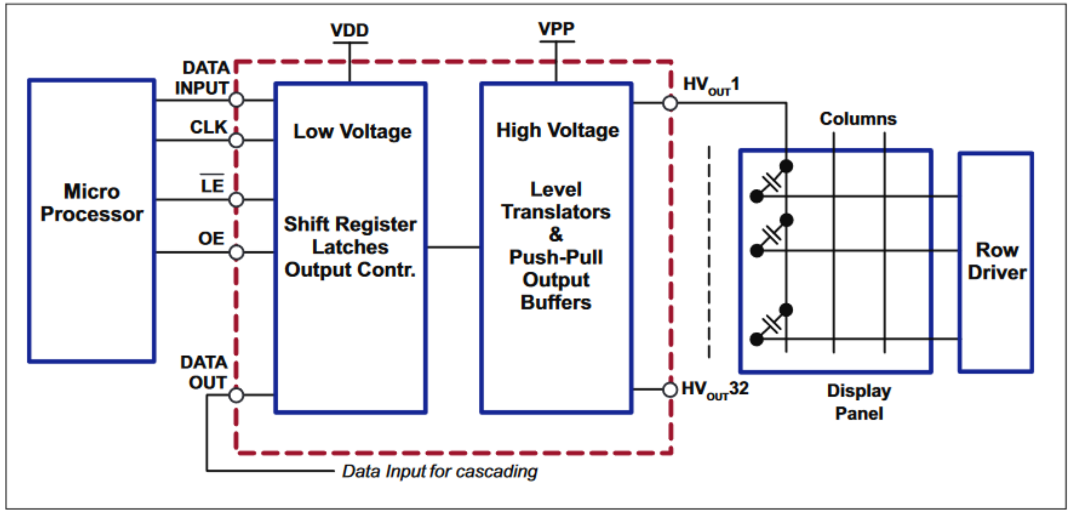
Consumes virtually no current in the tuning elements ✓

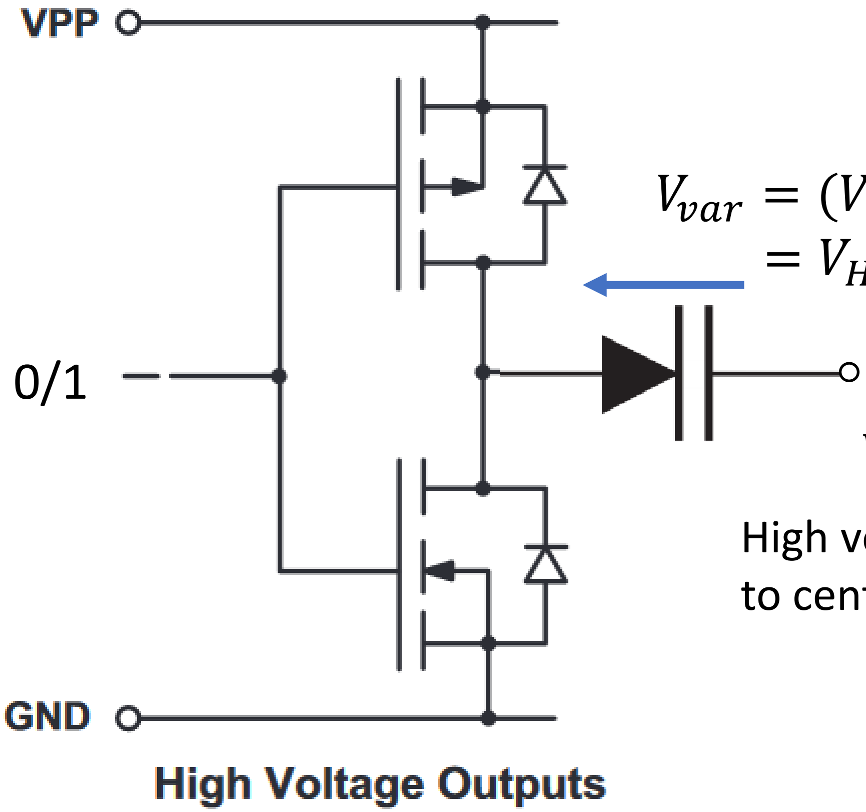
Solution: HV5308 high voltage serial to parallel converter



32 channels per IC – serving independent polarisations of 16 unit cells

Typical Application Circuit





$V_{var} = (V_H - V_{PP})$ (for 0)
$= V_H$ (for 1)

High voltage connected to central patch

Configuration circuitry

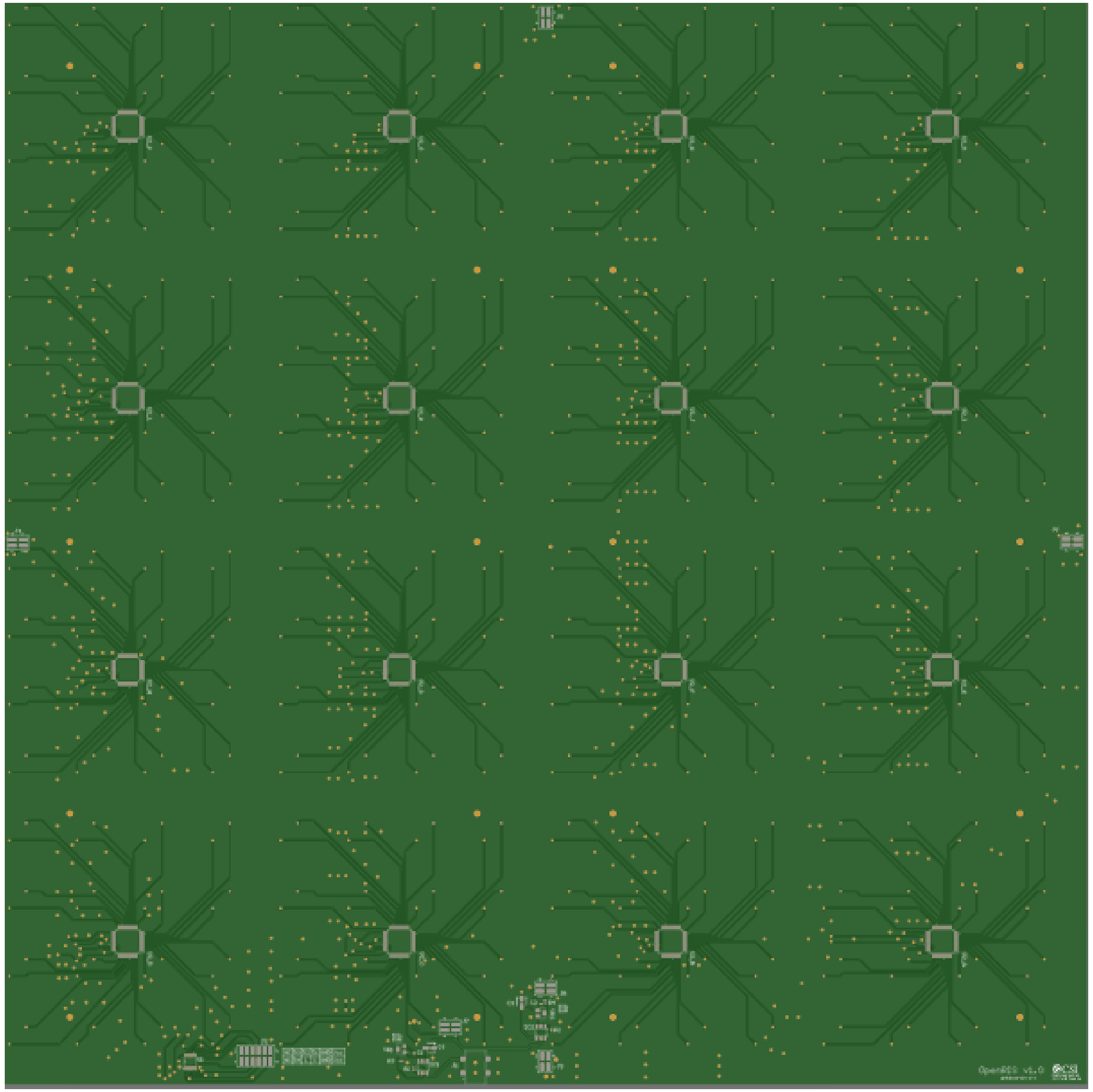
16 x 32-channel high voltage shift registers in push-pull configuration.

Two independent control voltages for each unit cell

Digital control via a serial interface. Compatible with any off-the-shelf microcontroller system.

Operating band set by 2 voltage levels determined by ultra-low power voltage regulators.

Each 256-element tile consumes less than 40 mW



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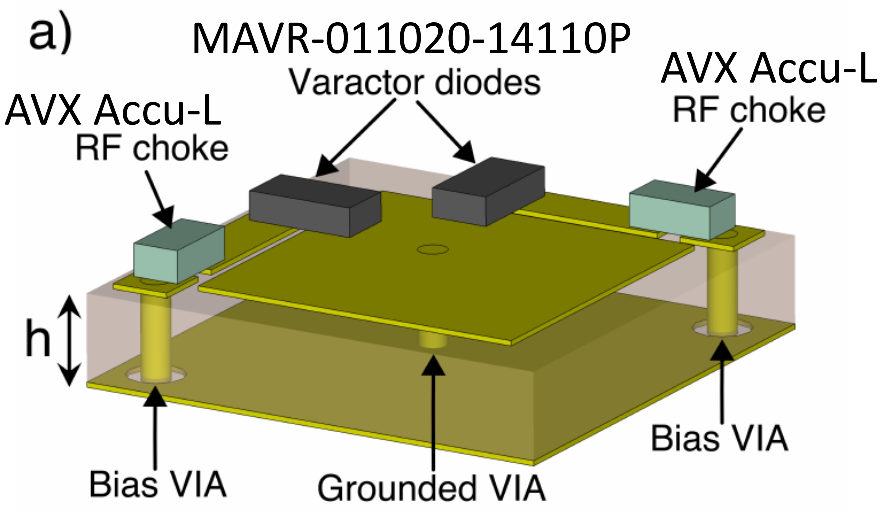
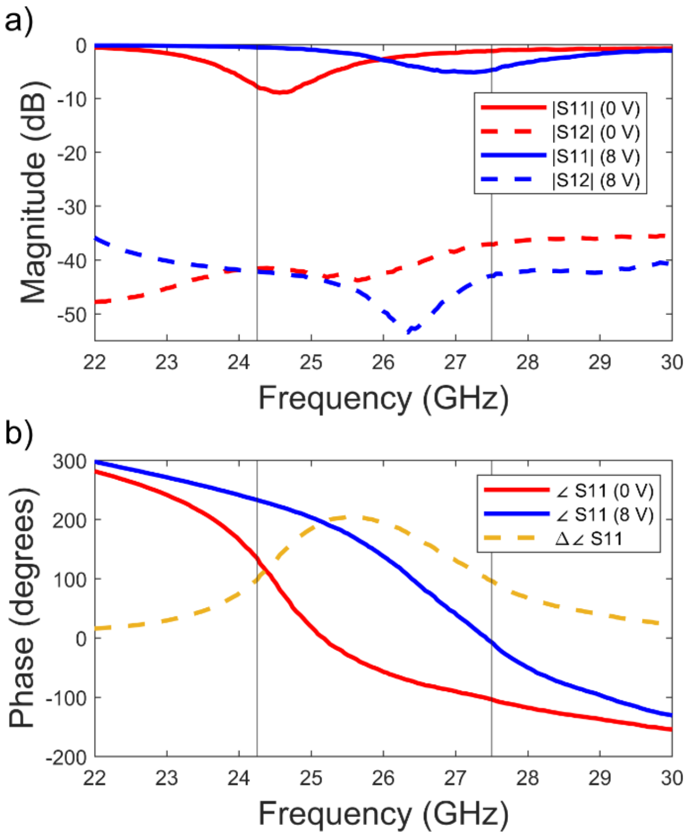
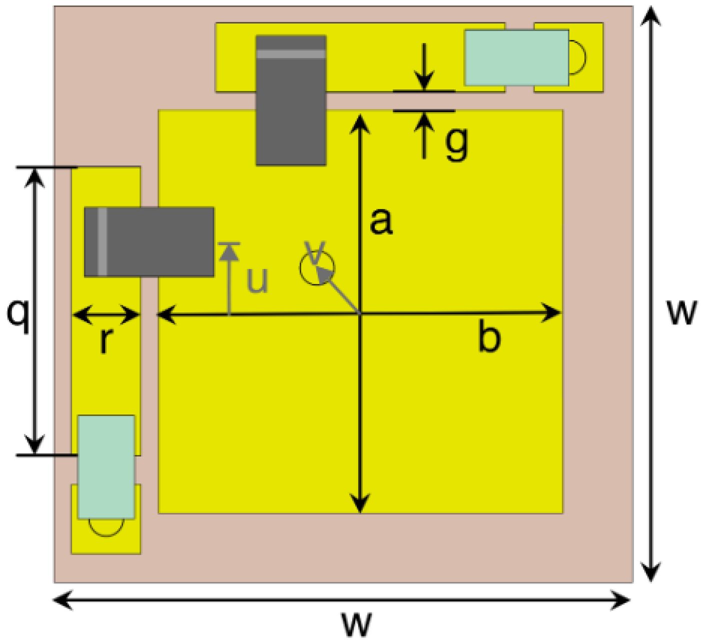
Scalability: design for European mmWave 5G band 24.25 - 27.5 GHz







Parameter	Length (mm)	Parameter	Length (mm)
w	3.1	h	0.6
g	0.1	a, b	2.2, 2.2
q, r	1.6, 0.4	u, v	0.4, 0.25

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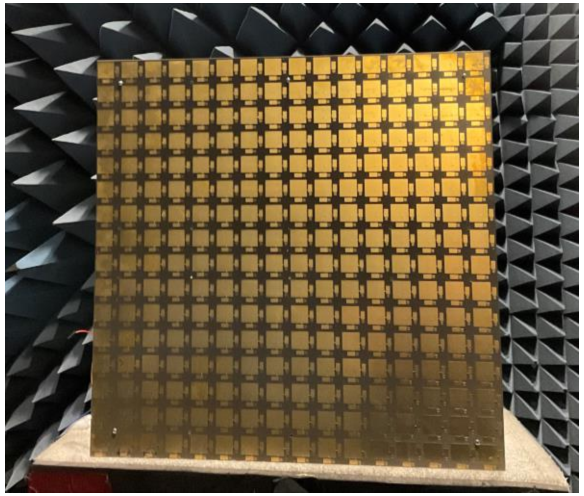
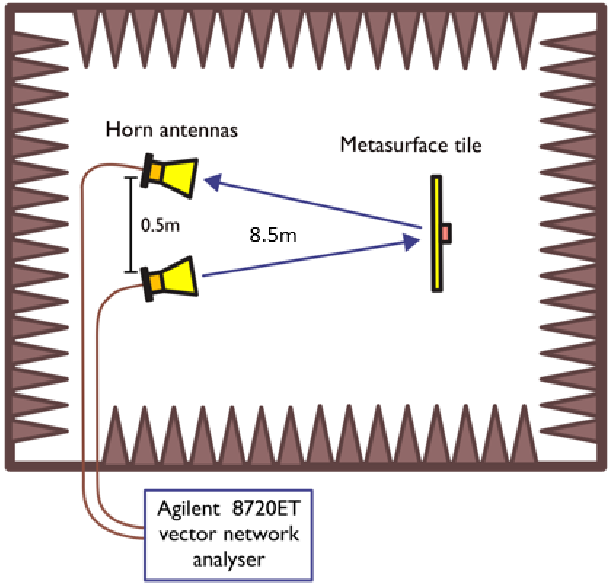
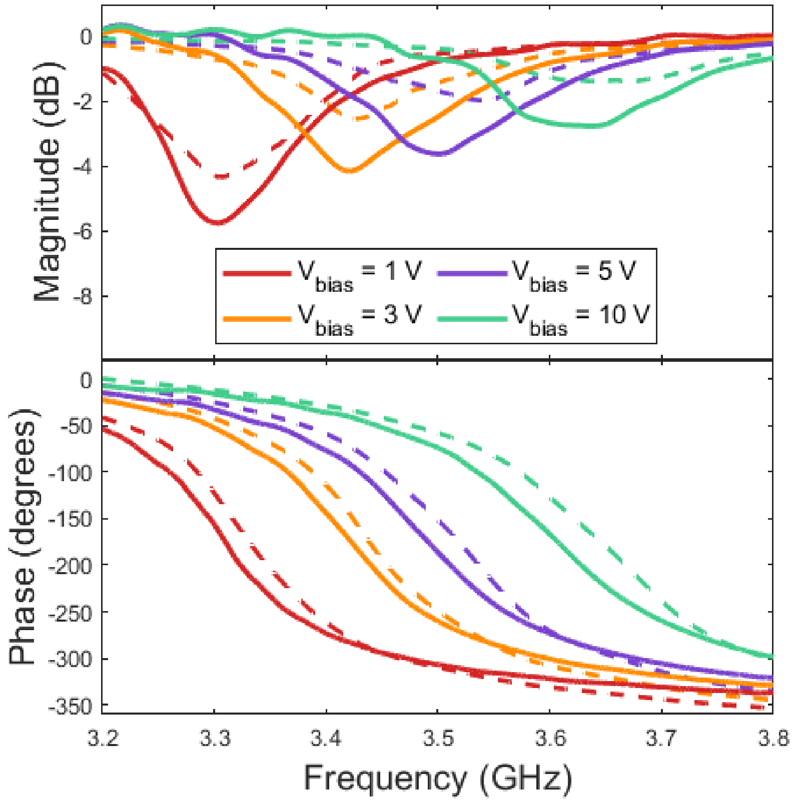
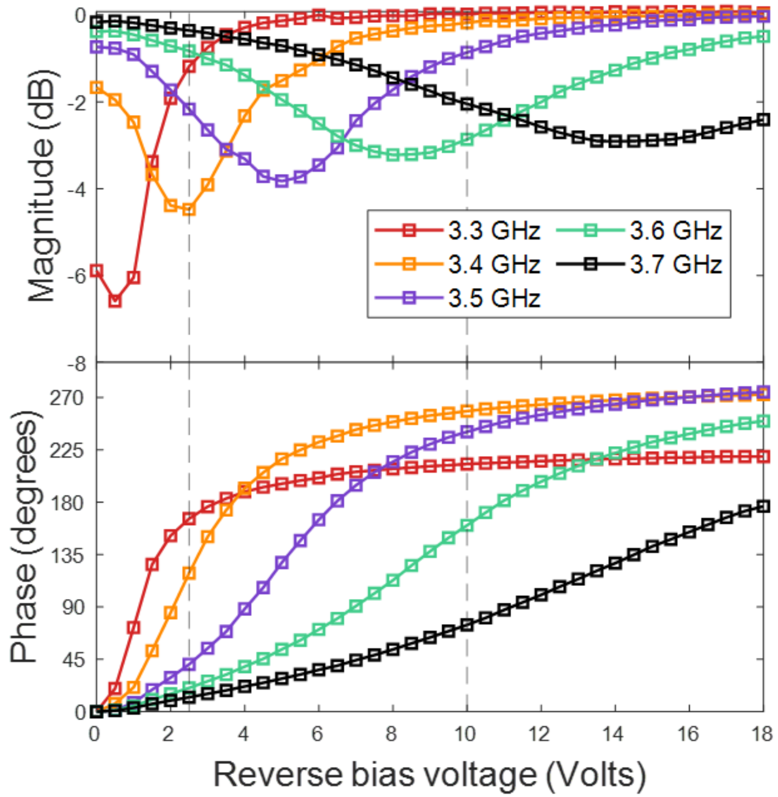
Global reflection measurements







Band tunability



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Far-field to far-field beamsteering performance

Configurations generated from a numerical approximation:

$$P_r = P_t \frac{G_t G_r d_x d_y \lambda^2}{64\pi^3} \times \left| \sum_{m=1-\frac{M}{2}}^{M/2} \sum_{n=1-\frac{N}{2}}^{N/2} \frac{\sqrt{F_{n,m}^{combine}}\,\Gamma_{n,m}}{r_{n,m}^{t} r_{n,m}^{r}} e^{\left(-j\frac{2\pi}{\lambda}\left(r_{n,m}^{t}+r_{n,m}^{r}\right)\right)} \right|^2$$

N = number of rows M = number of columns

$r_{n,m}^{q}$ = distance between transmitter/receiver and element (n,m)

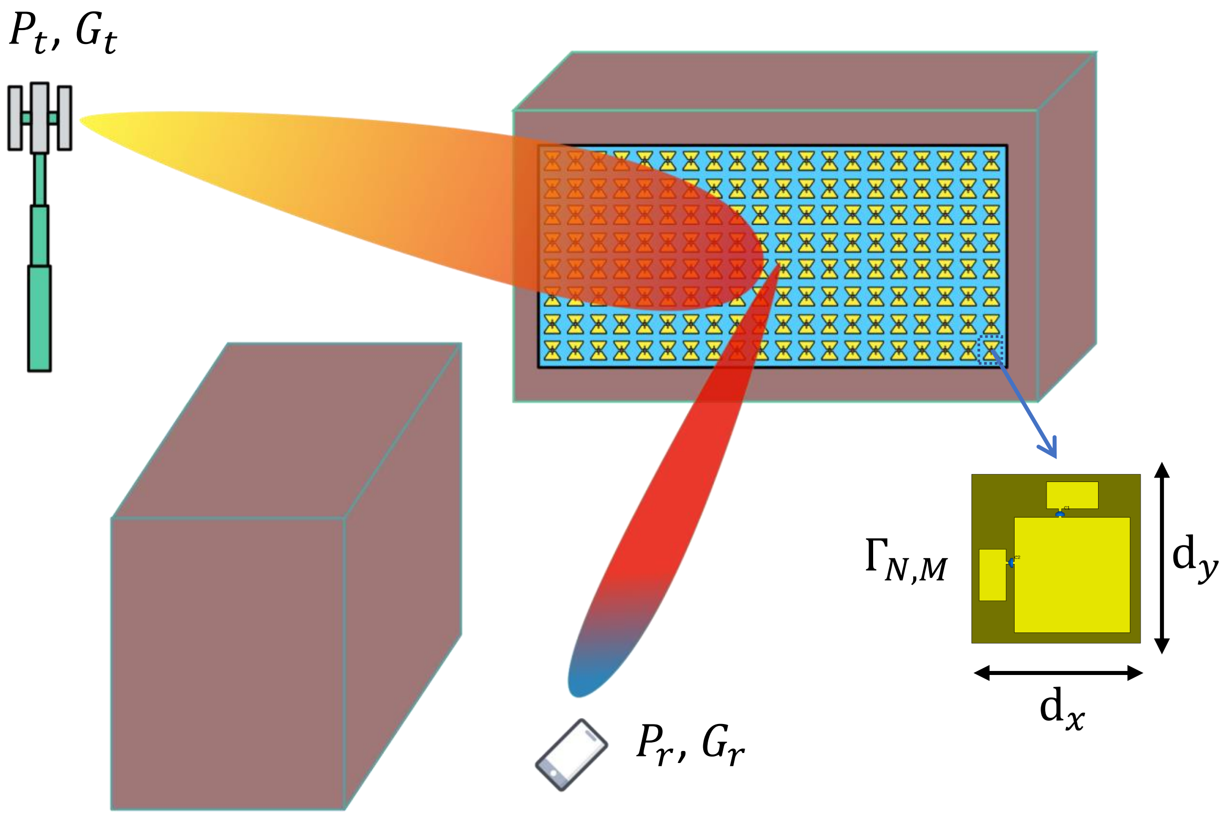
G_q = transmitter/receiver gain

G = unit cell gain

$F_{n,m}^{combine}$ = factor taking into account normalised transmitter, receiver, and unit cell radiation patterns

d_x and d_y = unit cell transverse dimensions

$\Gamma_{n,m}$ = reflection coefficient of unit cell (n,m)



V. D. Esposti et al., Reradiation and Scattering from a Reconfigurable Intelligent Surface: A General Macroscopic Model, *IEEE Transactions on Antennas and Propagation*, 2022

W. Tang *et al.*, Wireless Communications With Reconfigurable Intelligent Surface: Path Loss Modeling and Experimental Measurement, *IEEE Transactions on Wireless Communications*, 2021

Fully-Addressable Varactor-Based Reflecting Metasurface with Dual-Linear Polarisation for Low Power RISs

BT | University of Glasgow | CSI Communication, Sensing & Imaging

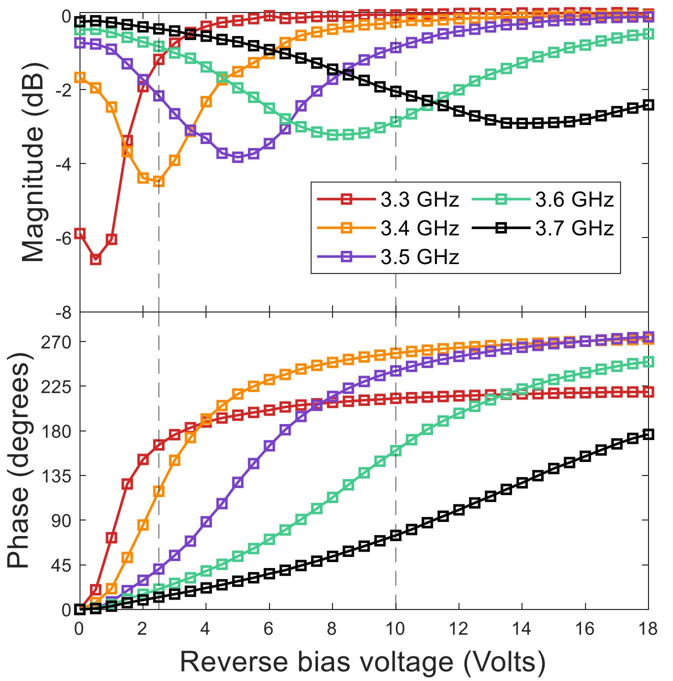
10.1109/TAP.2022.3149660
10.1109/TAP.2022.3216555

Beam pattern measurements

Configurations selected via:

$$P_r = P_t \frac{G_t G_r d_x d_y \lambda^2}{64\pi^3} \times \left| \sum_{m=1-\frac{M}{2}}^{M/2} \sum_{n=1-\frac{N}{2}}^{N/2} \frac{\sqrt{F_{n,m}^{combine}}\,\Gamma_{n,m}}{r_{n,m}^{t} r_{n,m}^{r}} e^{\left(-j\frac{2\pi}{\lambda}\left(r_{n,m}^{t}+r_{n,m}^{r}\right)\right)} \right|^2$$

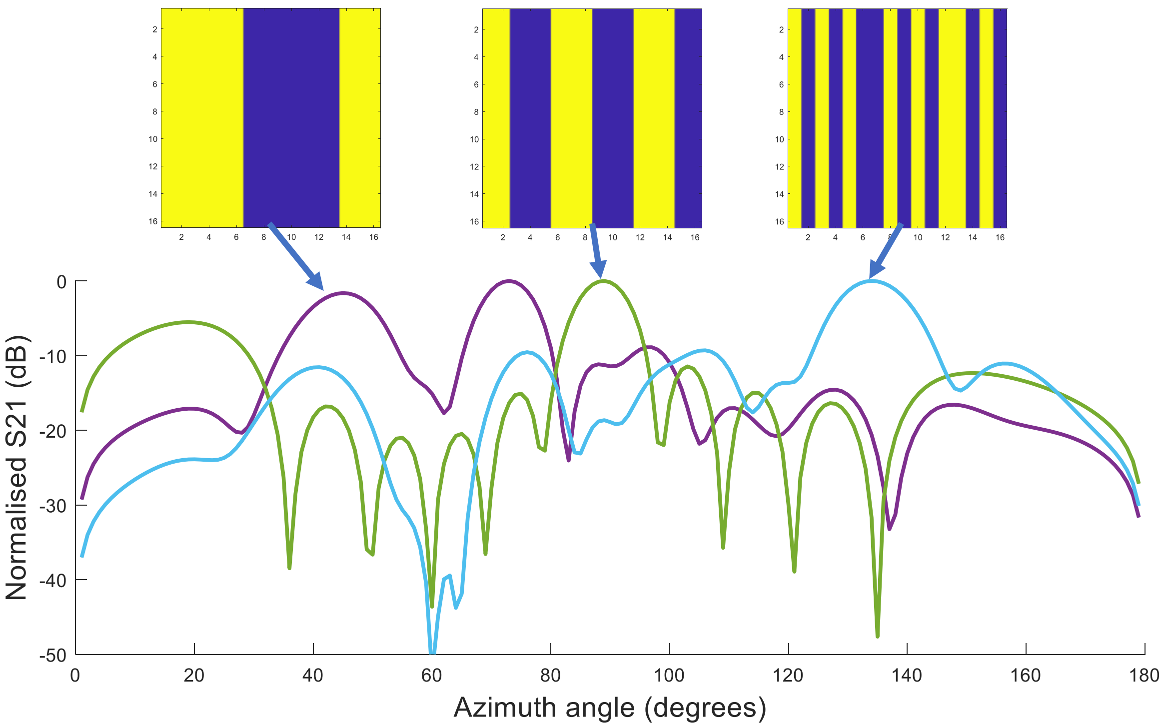
Γ selected from measured global reflection coefficients:



16 x 16 unit cells (0.48 m x 0.48 m)

Tx-RIS, Rx-RIS 100m

$\phi_{tx} = 120°$



Approximated reradiation patterns of single RIS tile

1-bit far-field to far-field will often result in a split beam due to pattern symmetry

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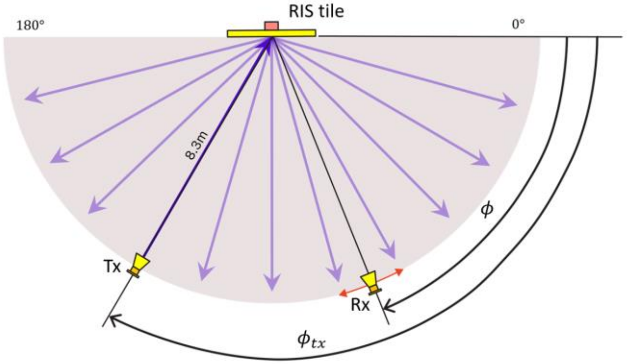
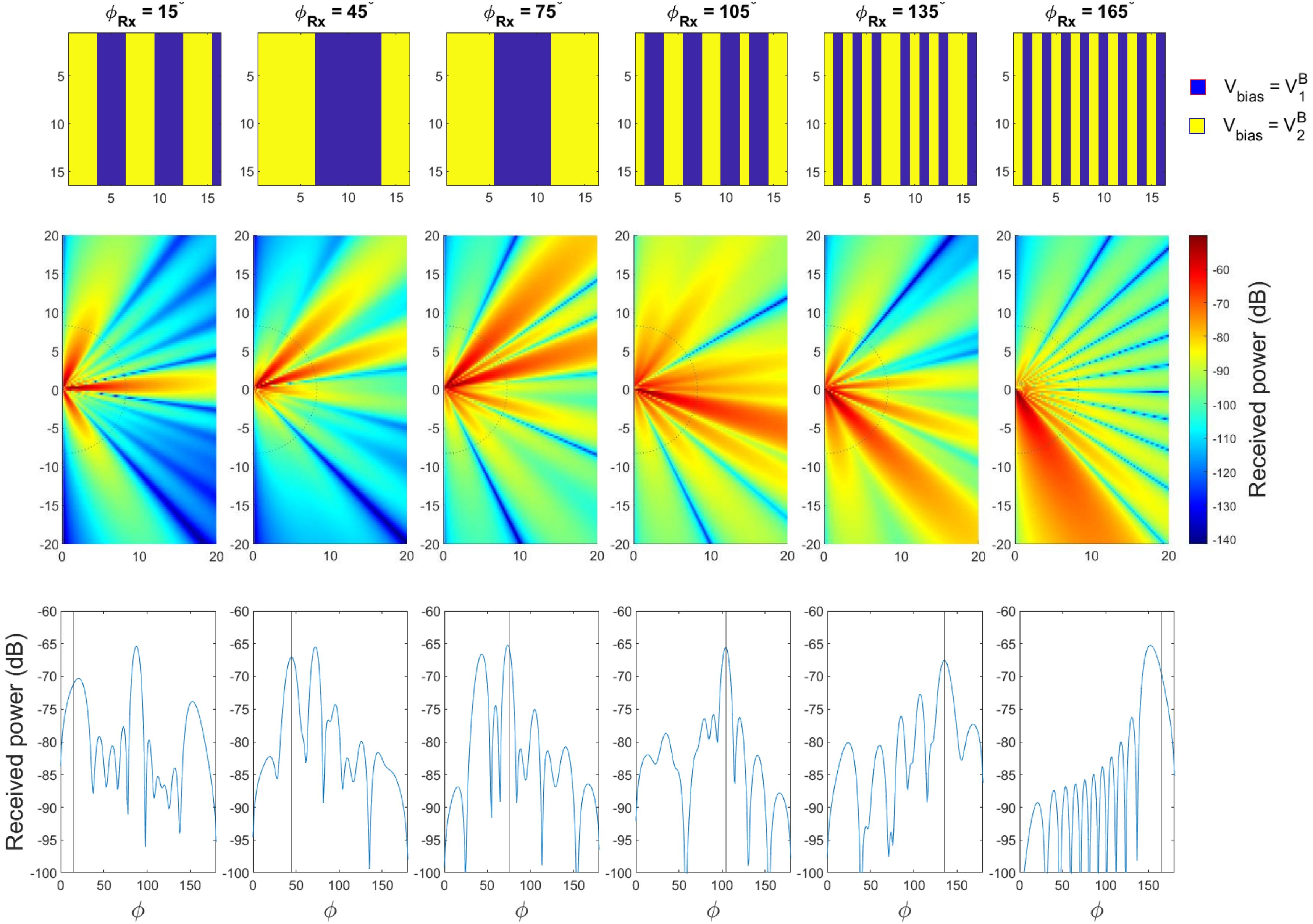
Codebook

Set of configurations to cover half-space at 15° steps

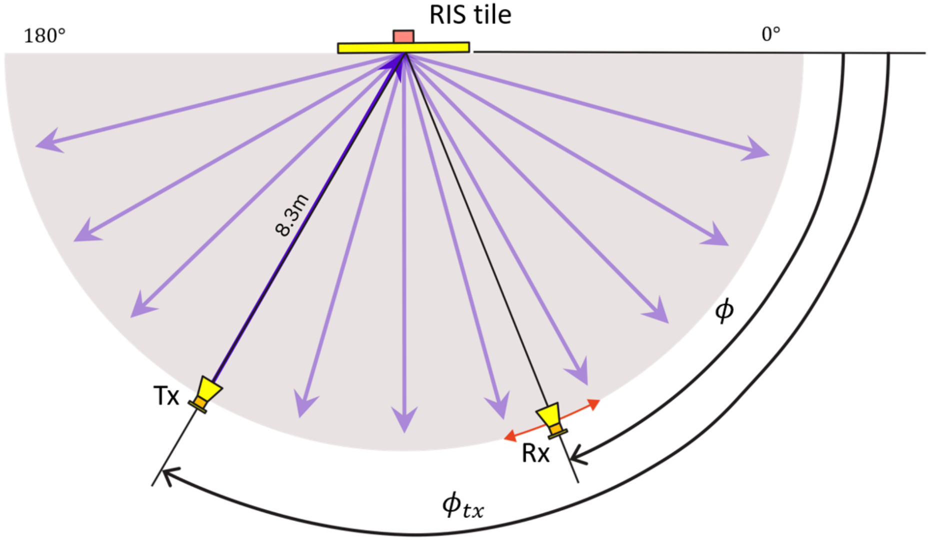
$\phi_{tx} = 120°$

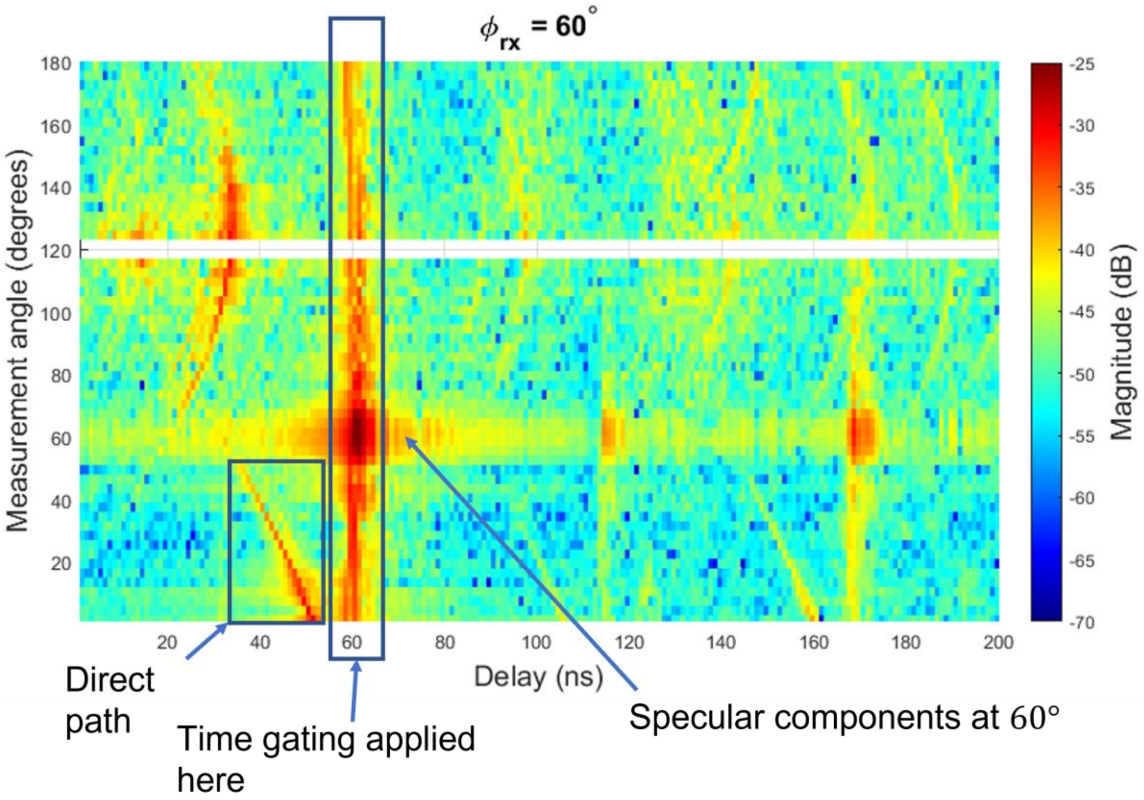




Fully-Addressable Varactor-Based Reflecting Metasurface with Dual-Linear Polarisation for Low Power RISs

Measurement setup





- Standard gain ridged horn antennas
- Keysight PNA vector network analyser
- Calibration plane at antenna ports
- Time gating applied to reduce multipath effects

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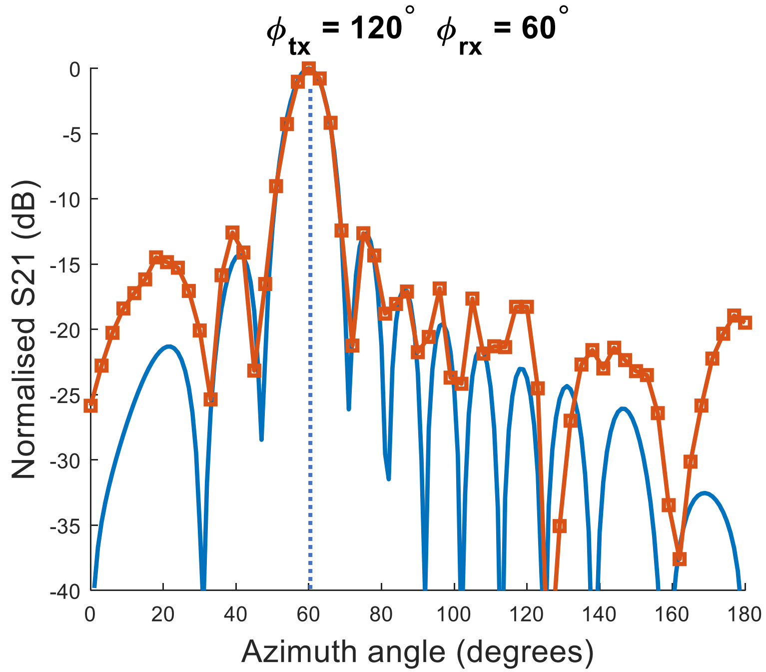
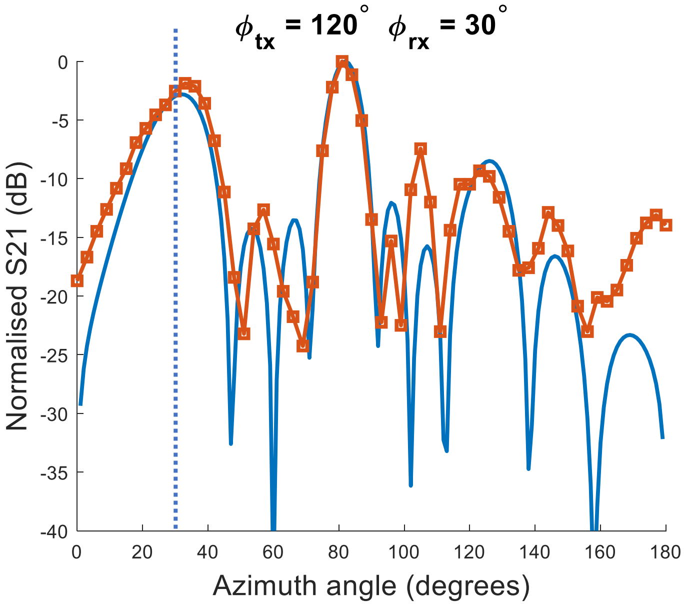
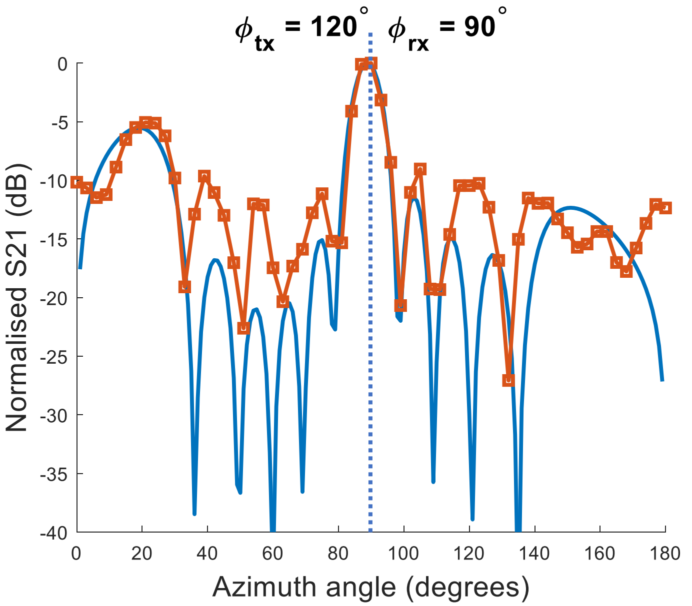
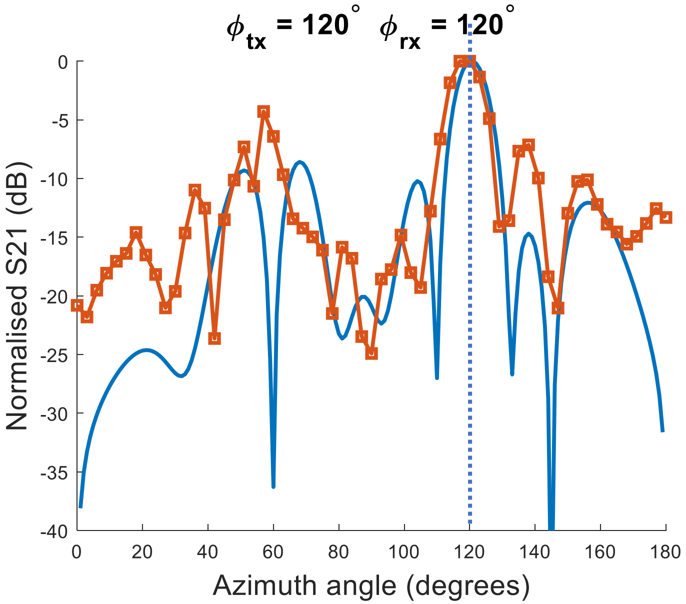
Results

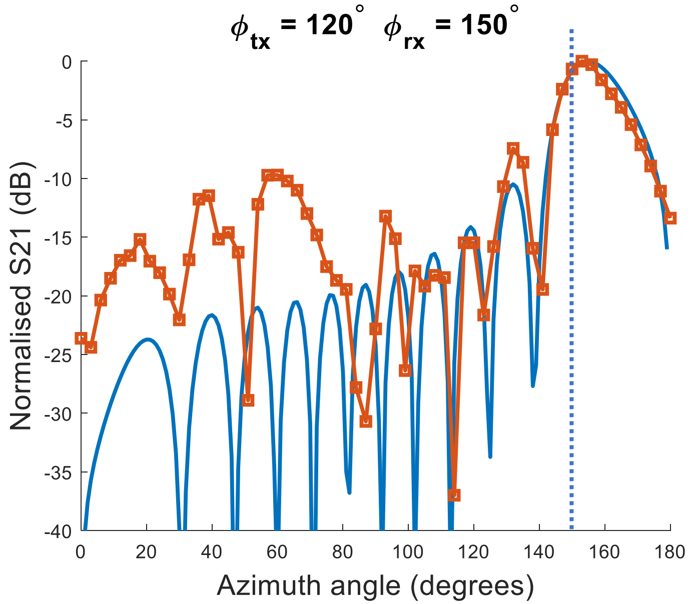


Specular reflection









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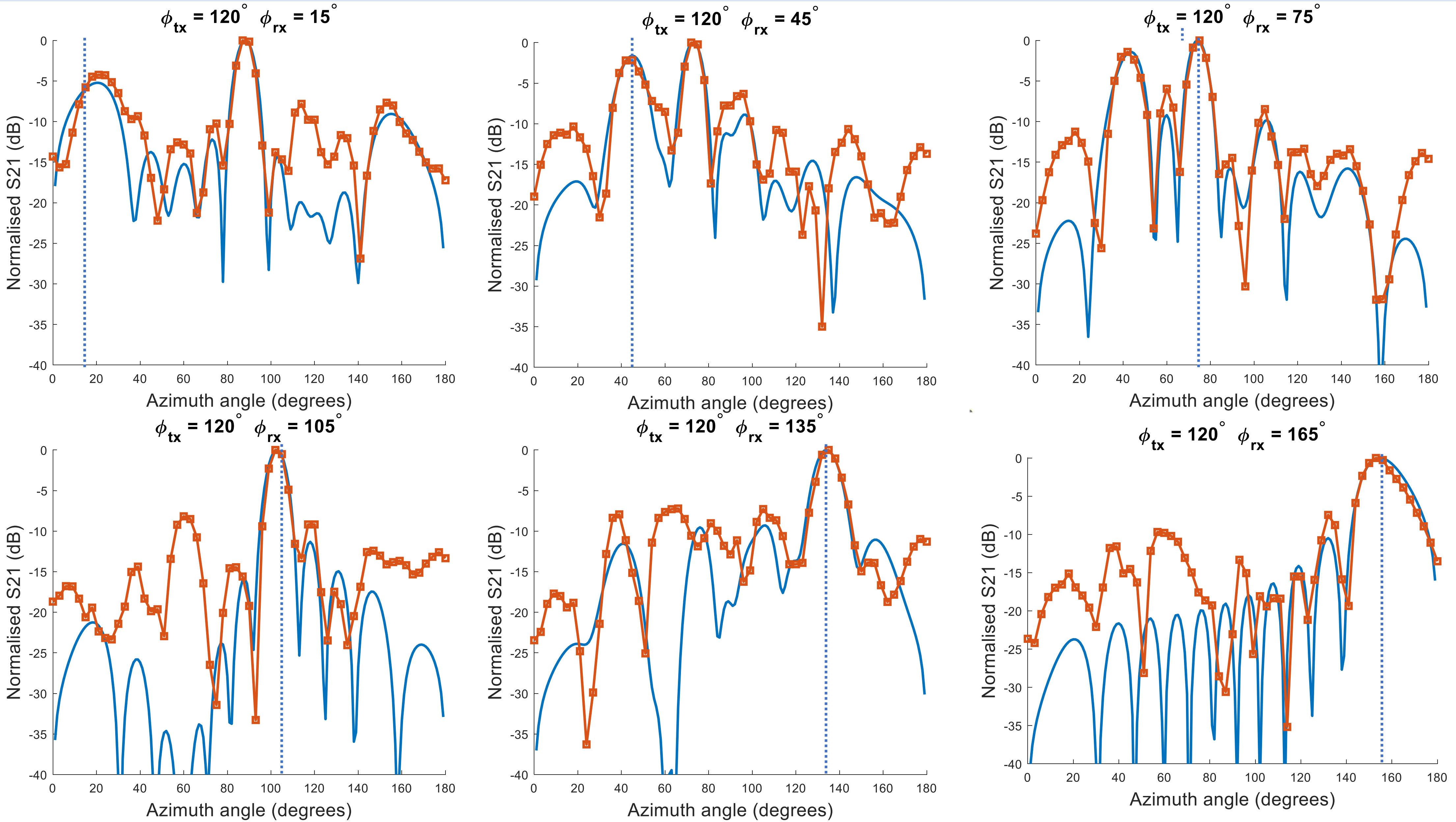
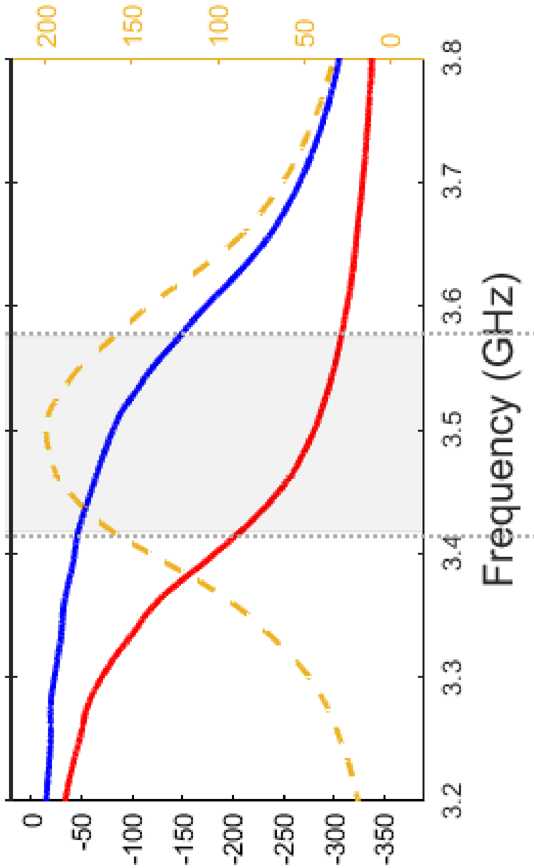
Results



Fully-Addressable Varactor-Based Reflecting Metasurface with Dual-Linear Polarisation for Low Power RISs

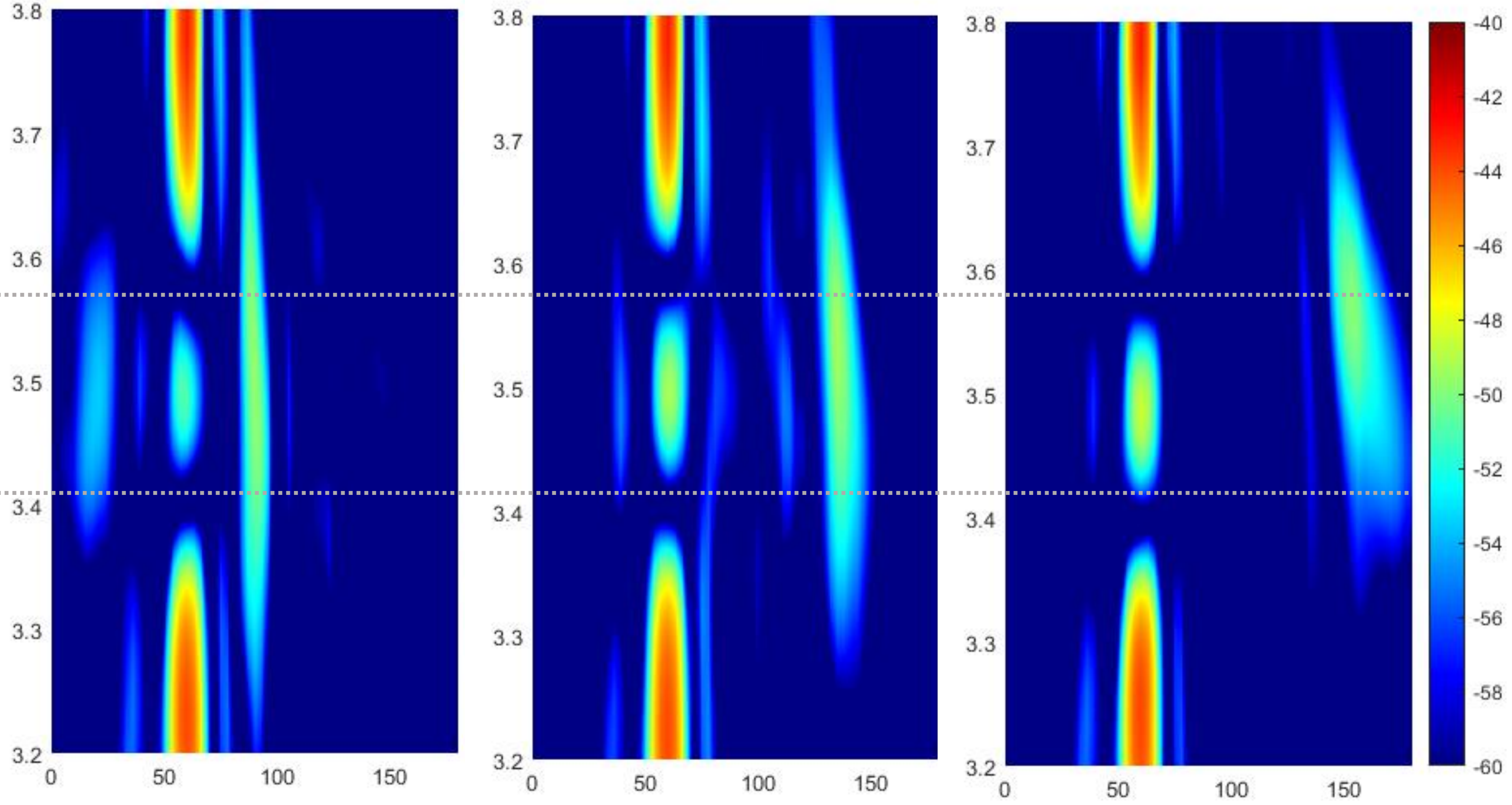
Instantaneous bandwidth

Operational voltages selected for maximum 1-bit bandwidth



Received power versus frequency versus azimuth angle for $\phi_{tx} = 120°$

$\phi_{rx} = 90°$ $\phi_{rx} = 135°$ $\phi_{rx} = 165°$



$BW_{3dB} = 335\ MHz$ $BW_{3dB} = 275\ MHz$ $BW_{3dB} = 210\ MHz$

Build your own RIS

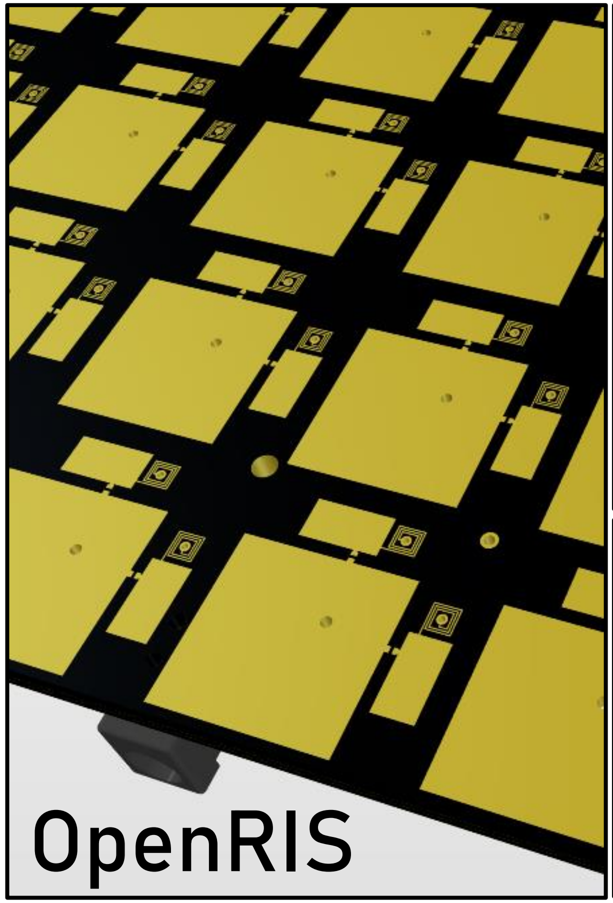
Documentation, schematics, measurement data, and code all available on GitHub.

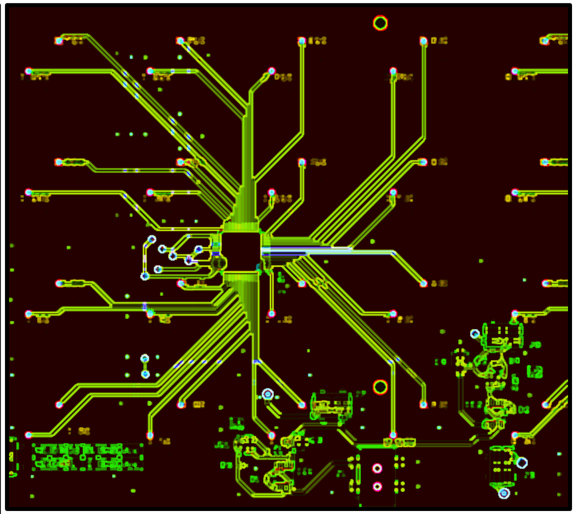
open source hardware

OpenRIS

GitHub

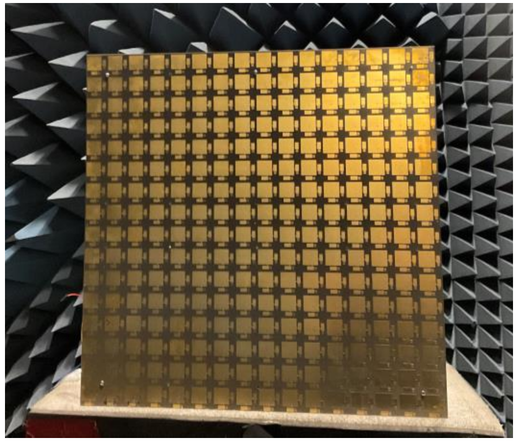
https://github.com/jimrains/OpenRIS





Questions

OpenRIS
GitHub



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