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Article

DESIGN OF CAVITY-BACKED FULL-MODE SUBSTRATE INTEGRATED WAVEGUIDE ANTENNA FOR X-BAND (10 GHZ) APPLICATIONS

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Abstract: This paper presents the design and analysis of a cavity-backed full-mode (FM) Substrate Integrated Waveguide (SIW) antenna operating in the X-band at 10 GHz. The proposed work is an extension of an earlier millimeter-wave design initially targeted at 30 GHz, which faced fabrication and measurement constraints. By scaling the design to 10 GHz, reliable fabrication and experimental feasibility are achieved while preserving the advantages of cavity-backed SIW structures, such as high front-to-back ratio, improved aperture efficiency, and enhanced gain. Furthermore, a four-element FM SIW cavity-backed antenna array arranged around a square patch is investigated to demonstrate beam steering through selective ON/OFF excitation and phase control. Simulation results confirm wide impedance bandwidth (~300 MHz), high port isolation (>30 dB), flexible beam steering, and stable radiation characteristics, making the proposed design suitable for X-band communication, sensing, and radar applications.

Keywords: Substrate integrated waveguide (SIW), cavity-backed antenna, X-band antenna, beam steering, antenna array, QMSIW Quarter Mode SIW

1. INTRODUCTION

Substrate Integrated Waveguide (SIW) technology has emerged as a promising solution for realizing compact, planar, and high-performance microwave and millimeter-wave components. SIW antennas combine the low-loss and high-quality factor characteristics of conventional waveguides with the ease of integration offered by planar circuits. Cavity-backed SIW antennas, in particular, offer enhanced front-to-back ratio (FBR), reduced surface wave losses, and improved radiation efficiency.

In earlier work, a full-mode cavity-backed SIW antenna was designed for millimeter-wave operation at 30 GHz by scaling the geometry of a 3.5 GHz quarter-mode (QM) SIW antenna. Although the design concept was validated through simulations, fabrication tolerances and measurement limitations at millimeter-wave frequencies posed significant challenges. To overcome these issues, the present work focuses on redesigning the antenna for X-band operation at 10 GHz. This frequency shift ensures reliable fabrication using standard PCB processes and enables accurate experimental characterization using readily available measurement setups.

This paper details the design methodology, performance analysis of a single-element FM SIW cavity-backed antenna, and the development of a four-element antenna system capable of beam steering through selective excitation and phase control.

Antenna Design and Operating Principle

Full-Mode SIW Cavity Configuration

The proposed antenna employs a full-mode SIW cavity designed to support the dominant TE$_{10}$$ mode at 10 GHz. The cavity is realized using two rows of metallized vias that emulate the sidewalls of a conventional rectangular waveguide. A metallic cavity backing is introduced to suppress back radiation and surface wave propagation.

An optimized slot/aperture is etched on the top metal layer to facilitate efficient radiation while maintaining structural integrity. The cavity-backed configuration significantly enhances the front-to-back ratio and overall radiation efficiency.

Design Calculations

Calculation of SIW antenna parameters at frequency 10 GHz

Cavity Design

$$f_{rmn0}= \frac{c}{2\sqrt{\epsilon r}}\sqrt{\left(\frac{m}{weff}\right)^2+\left(\frac{n}{Leff}\right)^2}$$

Dominant mode in cavity TE $_{110}$ where

$$f_{r110}= \frac{c}{2\sqrt{\epsilon r}}\sqrt{\left(\frac{1}{weff}\right)^2+\left(\frac{1}{Leff}\right)^2}$$

where W eff = effective width, Leff = effective length, fr =3.5 GHz

$$L_{eff}=L-\frac{D^2}{.95\,p} \qquad W_{eff}=W-\frac{D^2}{.95\,p}$$

Where L= length of substrate W = width of the substrate

D=diameter of Via, P = distance between 2 vias

for minimum leakage and in SIW

$$\frac{D}{S} <= 0.5 \qquad D = 1\text{ mm},\ S = 2\text{ mm},\ \frac{D}{S} = .5$$

for square cavity $L_{eff} = W_{eff}$

$$f_{r_{110}}= \frac{c}{2\sqrt{\epsilon r}}\sqrt{\left(\frac{1}{L_{eff}}\right)^2+\left(\frac{1}{L_{eff}}\right)^2}$$

$$= \frac{c}{2\sqrt{\text{€}r}} \sqrt{\frac{2}{L_{eff}^2}}$$

Where C = 3 x10 ^{8} m/s, €r = 2.2 (for RT DUROID 5880 substrate)
To resonate cavity at fr_{110} = 10 x 10^9 Hz = 10 GHz, Let us calculate length
when we cut the slot, f_r changes therefore it is always better to take lower f_r.
Design cavity by taking fr = 10 GHz.
Calculate length L for f r = 10 GHz.

$$f_{r_{110}} = \frac{c}{2\sqrt{\text{€}r}} \sqrt{\frac{2}{Leff^2}}$$

$$\frac{2\sqrt{\text{€}r}\ X\ f_{r_{110}}}{c} = \sqrt{\frac{2}{Leff^2}}$$

Squaring both sides

$$\left(\frac{2\sqrt{\text{€}r}\ X\ f_{r_{110}}}{c}\right)^2 = \frac{2}{Leff^2}$$

$$\left(\frac{2\sqrt{\text{€}r}\ X\ f_{r_{110}}}{c}\right) = \frac{\sqrt{2}}{Leff}$$

$$(L_{eff}) = \frac{\sqrt{2}\ X\ c}{2\sqrt{\text{€}r}\ X\ f_{r_{110}}}$$

$f\ r_{110}$ = 10 GHz c = 3 X 10^8 m/s €r = 2.2 (for RT DUROID 5880 substrate)

$$L_{eff} = \frac{\sqrt{2}\ X\ 3\ X\ 10^8}{2\sqrt{2.2}\ X\ 10\ x\ 10^9}$$

$$= .0167 \text{ m}$$

$$= 16.70 \text{ X } 10^{-3} \text{ m} = 16.70 \text{ mm} \cong 17 \text{ mm}$$

Hence $L_{eff} = W_{eff}$=17 mm

Now calculate dimension of substrate (PCB)

$$L_{eff} = L - \frac{D^2}{.95s} \qquad D = 1 \text{ mm, s} = 2 \text{ mm}$$

$$L = L_{eff} + \frac{D^2}{.95\ s}$$

$$L=17 + 526.3 \text{ X}10^{-3} \text{ m} = 17 \text{ mm} + .526 \text{ mm} = 17.526 \text{ mm}$$

but in Simulation it is taken as 20 mm for better fabrication optimized length = 20 mm.

Table 1. Design Parameters of 10 GHz Antenna obtained from calculations.
(The final dimensions of square SIW cavity resonators)

Parameters	Abbrevation	Dimension
Length of Substrate	Sub_L	20 mm
Width of Substrate	Sub_W	20 mm
Patch Length	Patch_L	18 mm
Patch Width	Patch_W	18 mm
Vias Vertical (20/2 =10)	n	9 nos
Center to Center Distance between via holes	s	2 mm
Diameter of Via Hole	d	1 mm
Slot length	Slot_l	10.7 mm
Slot width	Slot_w	2 mm
Feed Length	Fw	4.8 mm
Inset Cut width	Gw	0.5 mm

Formula:

$$w = \frac{7.48 \times h}{e^{\left(Z_0 \frac{\sqrt{\varepsilon_r + 1.41}}{87}\right)}} - 1.25 \times t$$

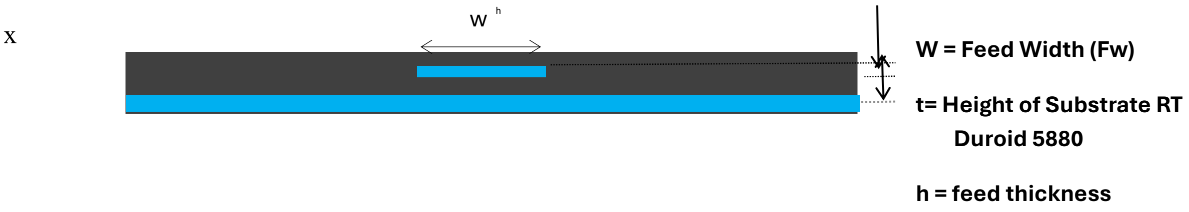
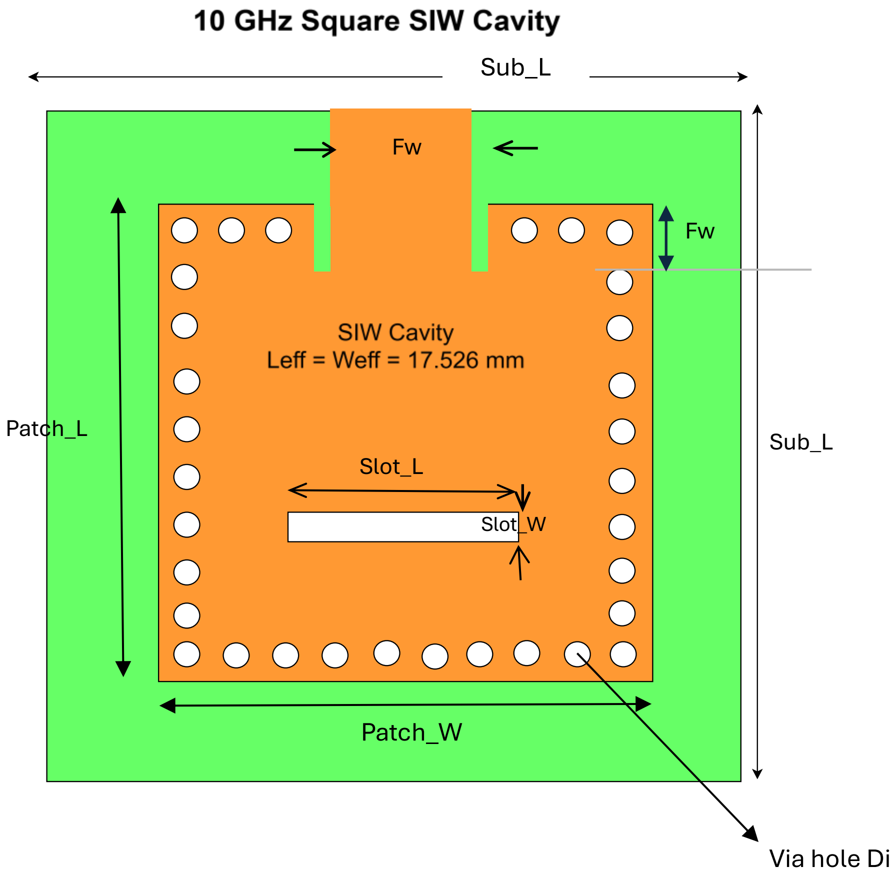


Figure 1. Width and Height calculation of Square shape SIW Antenna Single-Element Antenna Performance.



Abbr.	Dimension
Sub_L	20 mm
Sub_W	20 mm
Patch_L	18 mm
Patch_W	18 mm
n	9 nos
s	2 mm
d	1 mm
Slot_l	10.7 mm
Slot_w	2 mm
Fw	4.8 mm
Gw	0.5 mm

Figure 2. Single element 10 GHz Cavity backed Antennawith slotted structure.

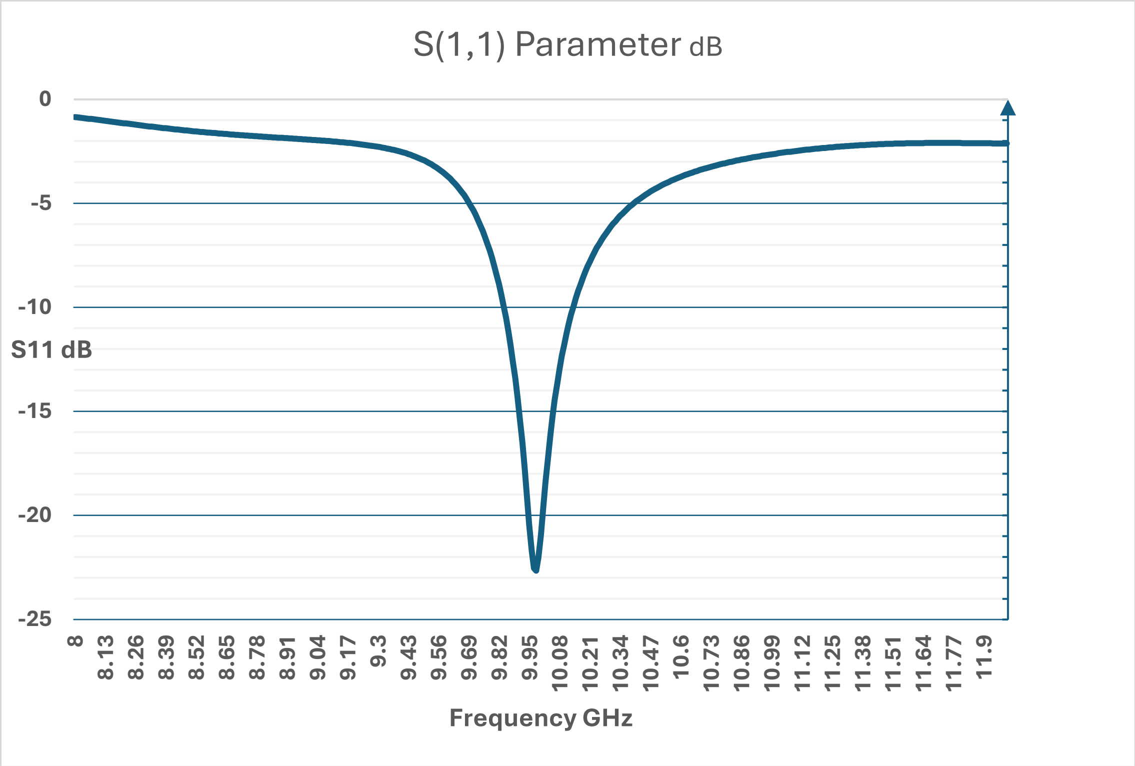


Figure 3. Simulated S parameter S11 response of the single-element antenna.

Geometry of the single-element cavity-backed FM SIW antenna.:-The optimized final dimensions for 10 GHz SIW cavity are Leff = Weff = 17.526 mm. The via hole diameter d is decided 1mm and adjacent vias spacing s decided 2mm. The coplanar waveguided feed line dimensions are calculated which also ensures 50 ohm impedance matching at the second port. The inset feed width was found to be Before going for open slot cutting on the patch. Fw = 4.8 mm, gap width Gw = 0.5mm, and inset cut length C_l=10.7 mm . Figure 3 shows the final realized square SIW cavity for the mm range at 10 GHz.

obtain the maximum radiation efficiency of the cavity-backed SIW antenna, the length of the open slot radiator should be equal to half the guided wavelength. [1]. This principle came from the fact that a slot antenna is equivalent to a complementary dipole antenna and hence half the guided wavelength becomes responsible for maximum radiation. considering the major impact of slot length which is also inversely proportional to the resonant frequency, it is required to have an accurate slot length at extremely high frequency.

Figure 4 indicates the return loss (log value of reflection coefficient) against the frequency plot. This shows the cavity is resonating near the desired frequency of 10 GHz ie 9.98 GHz. Even though the return loss value is lower, this still confirms the cavity's resonance. This is due to the sudden transition in impedance from the microstrip to the SIW cavity. The simulated performance of the single FM SIW cavity-backed antenna demonstrates a return loss bandwidth of approximately 300 MHz around 10 GHz. Fifure 5 shows that the antenna exhibits a stable radiation pattern with a gain of 4.95 dB at broadside (0°), a half-power beamwidth (HPBW) of 112°, and a front-to-back ratio of 22 dB.

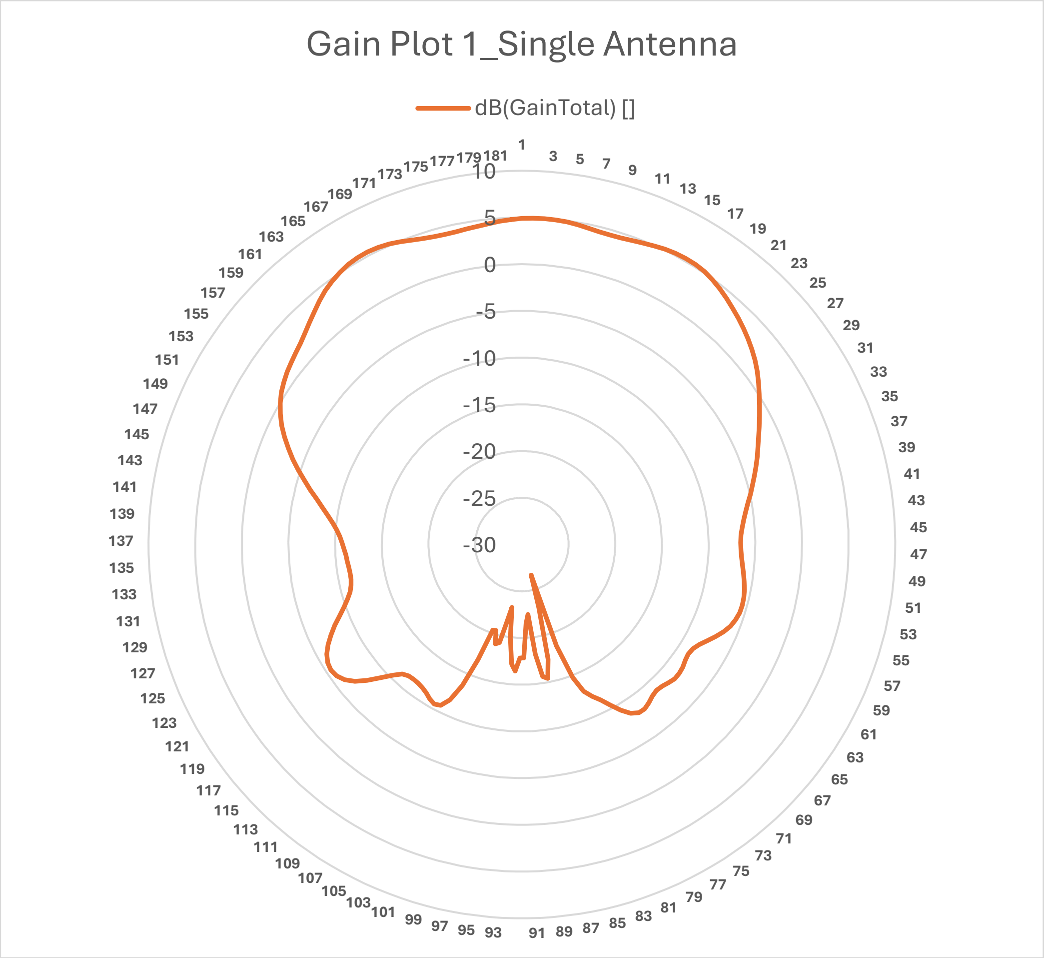


Figure 4. Radiation pattern and gain of the single-element antenna.

The figure shows a **polar radiation pattern** plotted on a circular (polar) coordinate system. The angular axis spans **0° to 360°**, marked with degree ticks around the perimeter, while the radial axis represents **normalized magnitude (in dB)**, decreasing toward the center. The –10 dB impedance bandwidth is 100 MHz, ensuring full coverage of the desired frequency band . Return loss – -15dB Return loss BW – 100MHz.

A **red curve** represents the measured or simulated response. The pattern is largely **directional**, with a **broad main lobe** oriented toward the top of the plot (approximately 0°), indicating the direction of maximum radiation or sensitivity. The response gradually decreases as the angle moves away from this direction.At the lower portion of the plot (around 180°), the pattern exhibits **deep nulls and multiple narrow side lobes**, suggesting reduced response and interference effects in the rear direction. The shape is asymmetric, indicating non-uniform radiation characteristics.

Four-Element FM SIW Cavity-Backed Antenna System

Array Configuration

To enhance radiation control and enable beam steering, four identical FM SIW cavity-backed antennas are arranged along the four sidewalls of a central square patch. This orthogonal placement provides spatial diversity and minimizes mutual coupling.

The four-element configuration achieves an impedance bandwidth of 300 MHz with excellent port isolation exceeding 30 dB between all antenna elements.

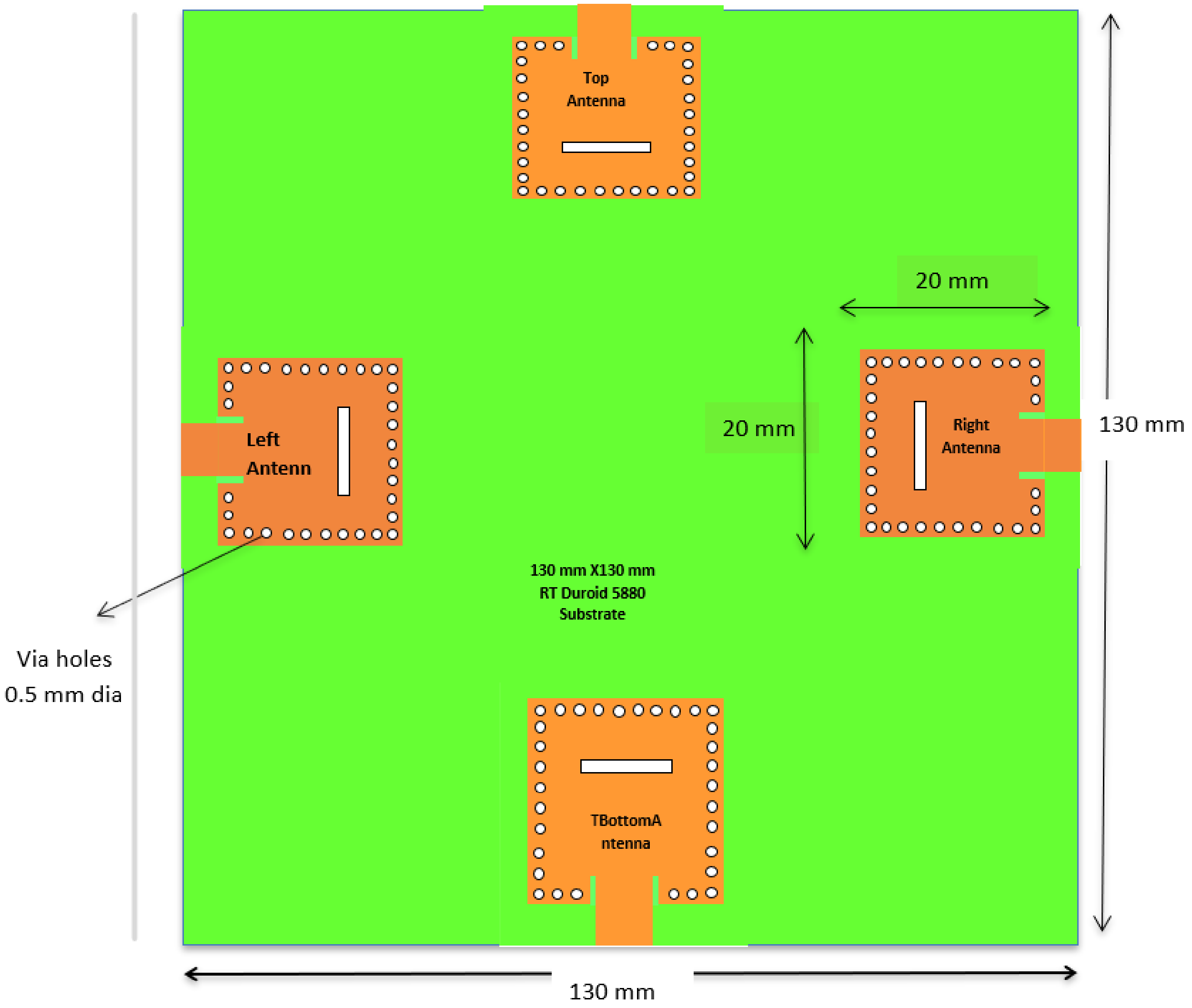


Figure 5. Configuration of the four-element FM SIW cavity-backed antenna system.

Isolation behavior: It is observed that isolation of >30dB across the bands and between all 4 antennae.

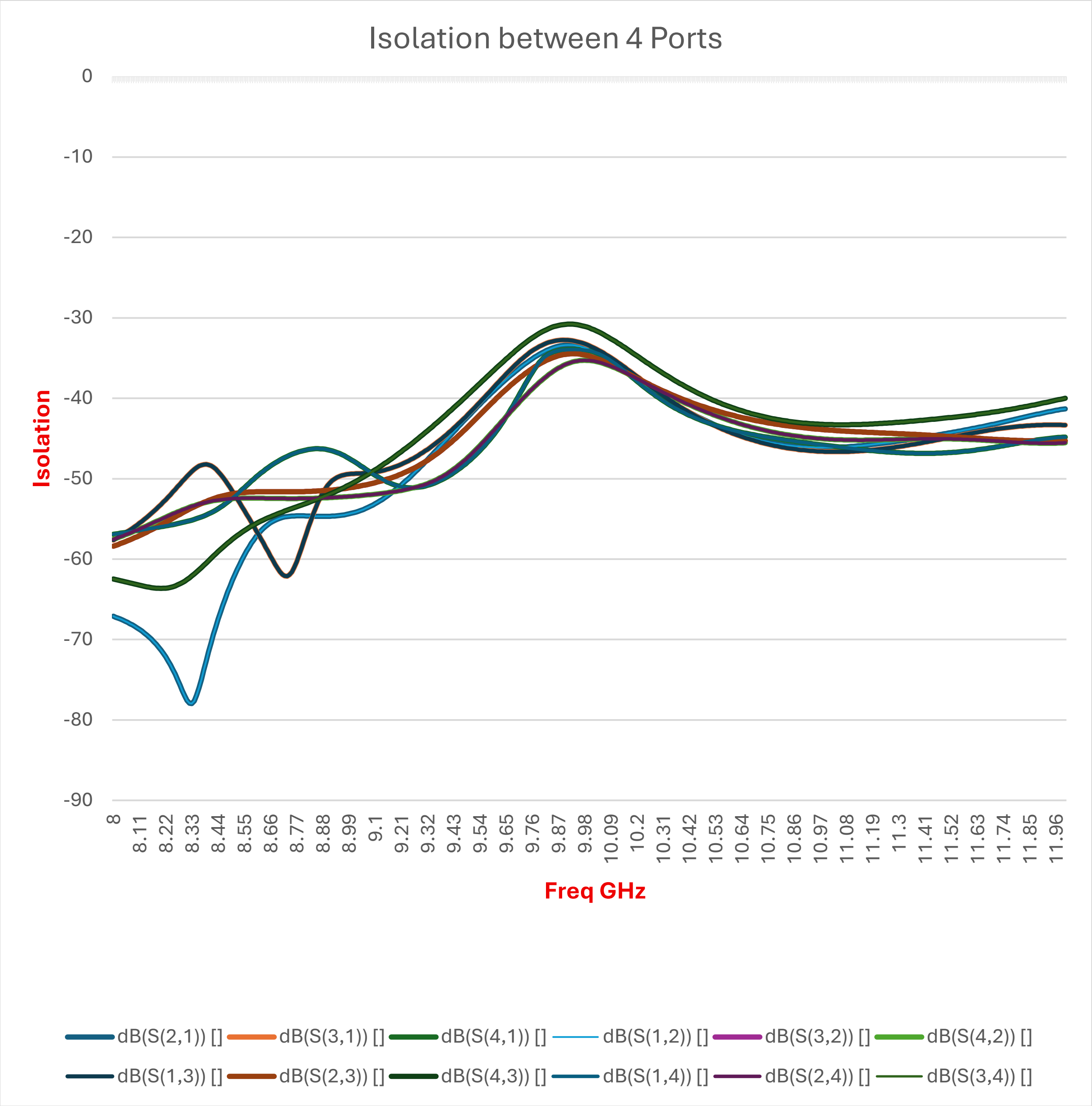


Figure 6. isolation plot.

The figure 7 shows an **isolation plot**, typically represented by **S21 (or S12)**, which describes how much power couples from one port of the RF system to another across **frequency (GHz)**. The vertical axis is **magnitude in dB**, and multiple colored curves correspond to **different design cases or operating conditions**.More **negative dB values indicate better isolation** (less unwanted coupling between ports). Values closer to 0 dB indicate stronger coupling.

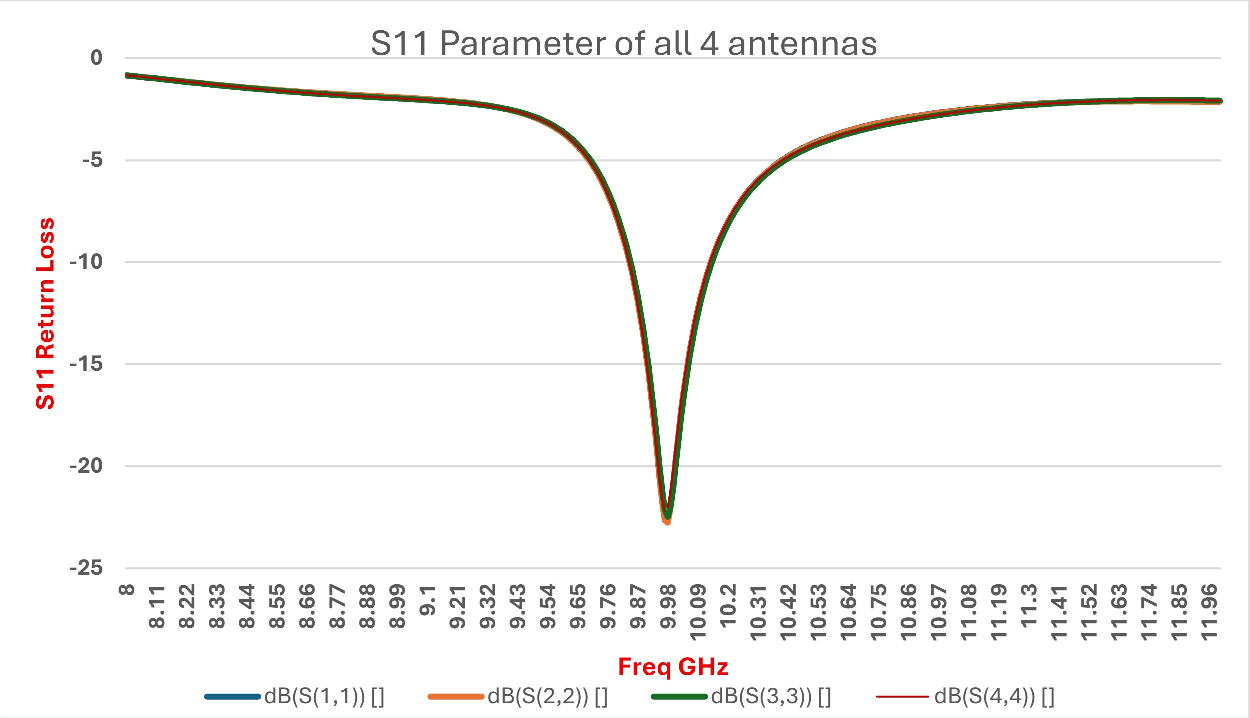


Figure 7. S11 parameter for different ON/OFF excitation cases.

The figure 8 shows an S-parameter plot (S11) labeled “S Parameter Plot 1”, representing the input reflection coefficient of an RF device as a function of frequency (GHz). The vertical axis is return loss (dB), while the horizontal axis is frequency. The plotted curves (different colors) correspond to multiple design cases or iterations, all showing very similar behavior, which indicates good design consistency. A deep notch is observed at the center frequency 10 GHz (marked on the plot). This notch corresponds to minimum S11, meaning very low reflected power and therefore excellent impedance matching at this frequency. The frequency markers highlight key points such as the resonant frequency and the –10 dB return-loss bandwidth, which is commonly used as the criterion for acceptable matching. This figure demonstrates that the system is **well matched at its resonant frequency**, with minimal reflection and good bandwidth performance. The close overlap of the curves suggests that the design is **stable and robust** across the compared configurations. Such an S11 response is typical and desirable in **antenna, RF front-end, and microwave circuit designs**, where efficient power transfer and controlled bandwidth are critical.

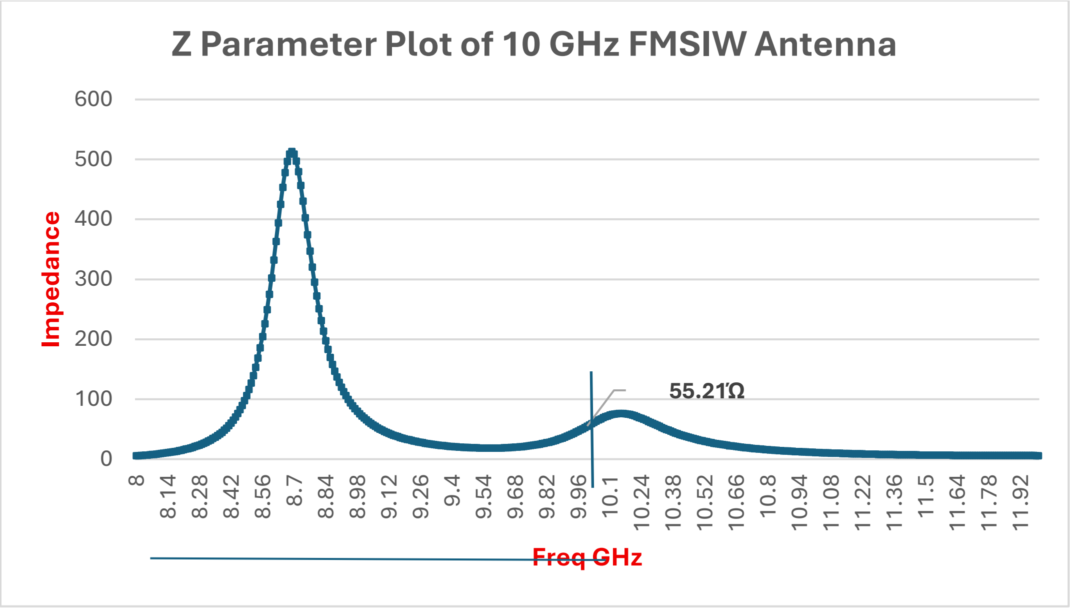


Figure 8. Z-parameter (impedance) versus frequency plot.

The figure 9 shows a Z-parameter (impedance) versus frequency plot, labeled "Z Parameter Plot 1." The horizontal axis represents frequency (GHz), while the vertical axis represents the magnitude of impedance (ohms). The red curve illustrates how the impedance of the system varies over the frequency range.

A prominent impedance peak is observed at the lower-frequency side of the plot. This sharp rise indicates a strong resonance or anti-resonance, where the structure exhibits very high impedance and stores energy rather than efficiently transferring it. Following this peak, the impedance rapidly decreases, indicating the system moving away from resonance. A smaller, broader peak appears at a higher frequency (highlighted by the marker) 10 GHz. This suggests a secondary resonance or higher-order mode, which is weaker and less sharp than the primary resonance. At frequencies away from these resonant points, the impedance remains relatively low and smooth, indicating more stable electrical behavior. This plot indicates that the system has **multiple resonant behaviors**, with one dominant resonance and a secondary mode at a higher frequency. Such impedance characteristics are common in **RF, microwave, or antenna systems**, where resonance locations strongly affect matching, bandwidth, and overall performance.

Beam Steering Using ON/OFF Control

Beam steering is achieved by selectively activating individual antenna elements or combinations thereof. Various excitation scenarios were investigated:- **Single Antenna ON:** Directional beams are obtained depending on the active sidewall element. Gains up to 7.8 dB are achieved with beam tilts of ±36°. **Achieving Beam Steering through ON/OFF Control.** In addition to phase control, **beam steering and radiation shaping** were successfully achieved by **selective ON/OFF activation** of the antennas.

Case 1: Single Antenna on Right Side wall is fed with input signal and remaining antenna not given input. isolation exceeding 30 dB between all antenna elements.

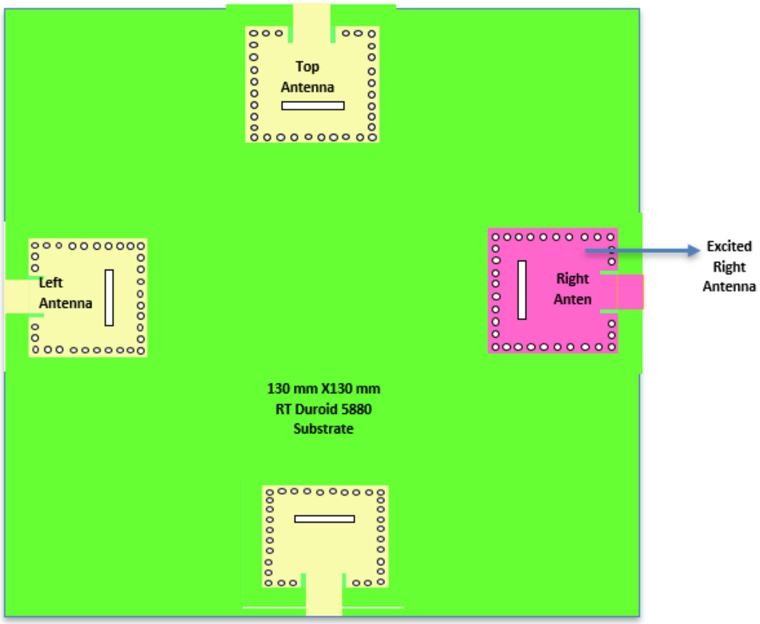


Figure 9. Single Antenna Excited – Right Side wall.

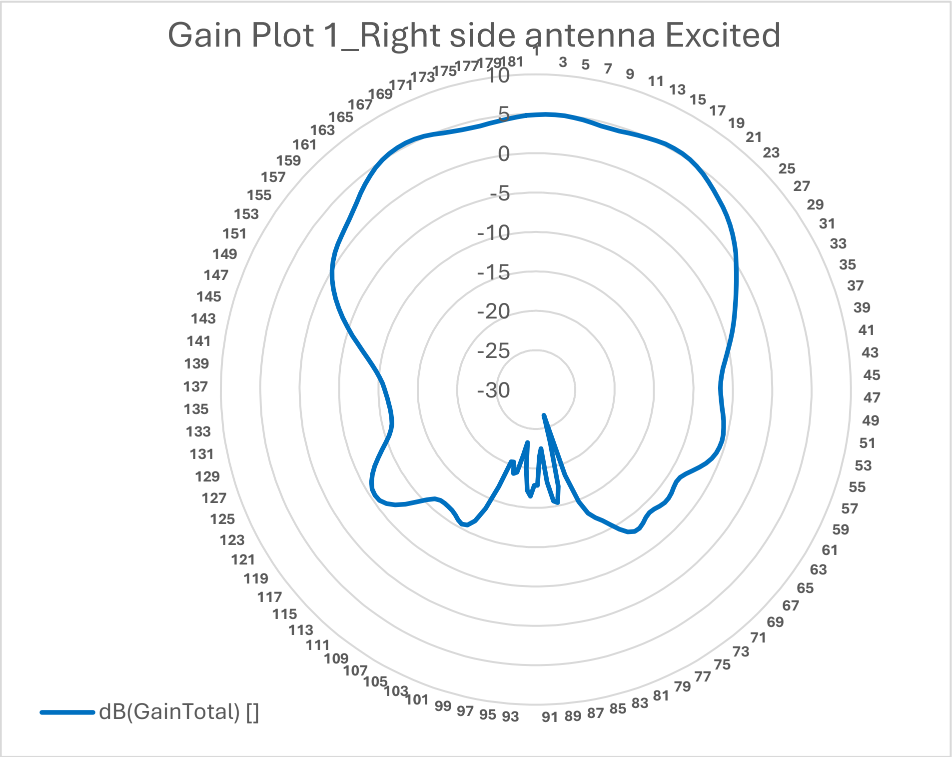


Figure 10. Radiation pattern and gain of the Single Right Side wall Antenna Excited(Max Gain at 0 de. 5.11 dB)

Case 2: Single Antenna on bottom side excited and remaining antenna off.

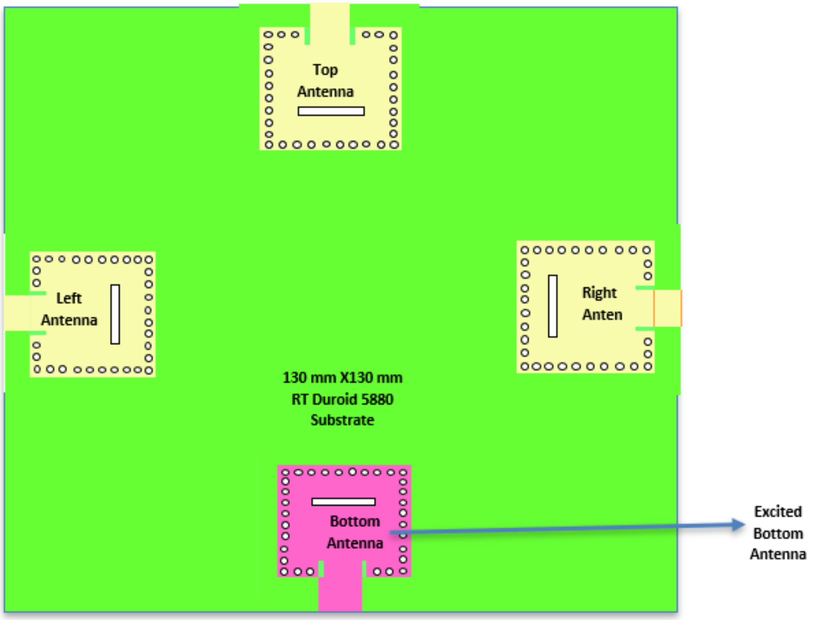


Figure 11. Single Antenna Excited – Bottom wall.

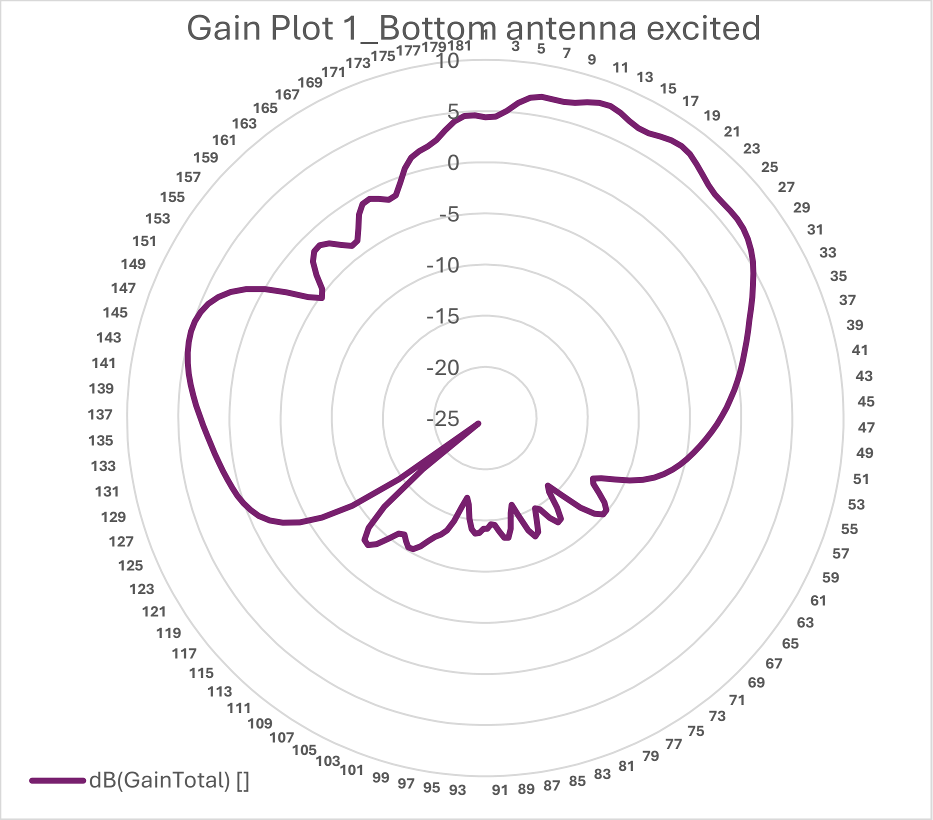


Figure 12. Gain plot when Single bottom antenna excited.

Gain observed when **Single bottom antenna excited. Max Gain obtained** 7.8 dB at 22 ^{0} – Top Right tilted. It is observed that the radiation pattern is **not perfectly symmetric**, implying an asymmetric antenna geometry, feed arrangement, or nearby structures affecting radiation. This plot demonstrates that the antenna exhibits **directional radiation behavior**, concentrating energy in a preferred direction while suppressing radiation elsewhere. Such a pattern is typical for **directional antennas**, where improved gain and reduced interference are desired.

Case 3: Single Antenna on Left Side wall is fed with input signal and remaining antenna not excited

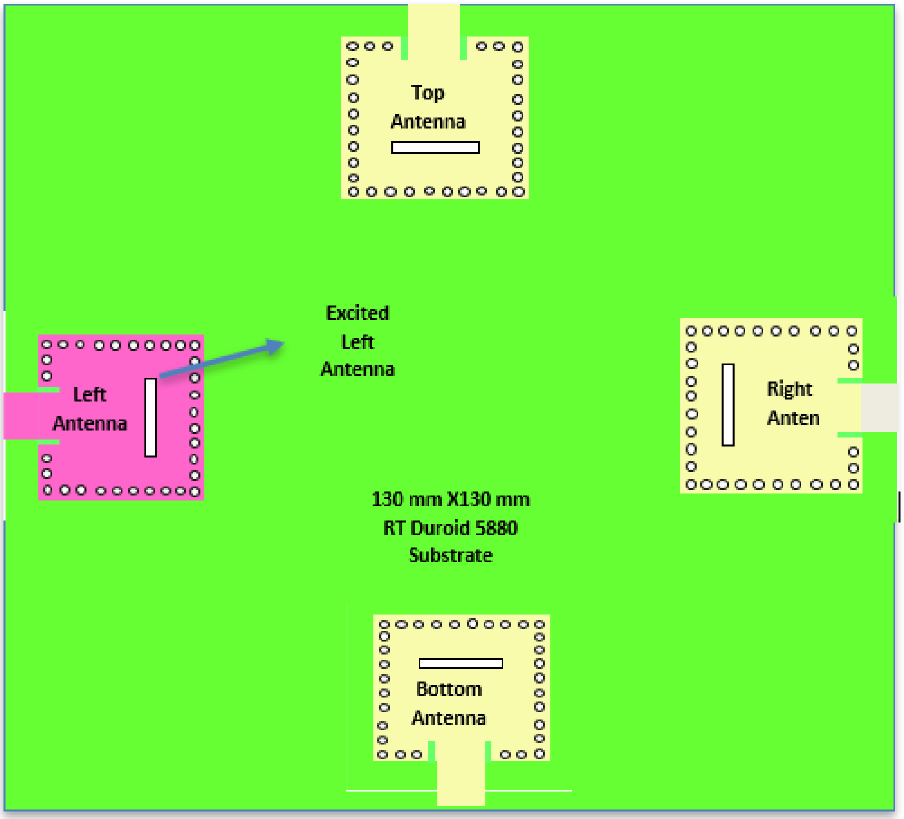


Figure 13. Single Antenna on Left sidewall excited.

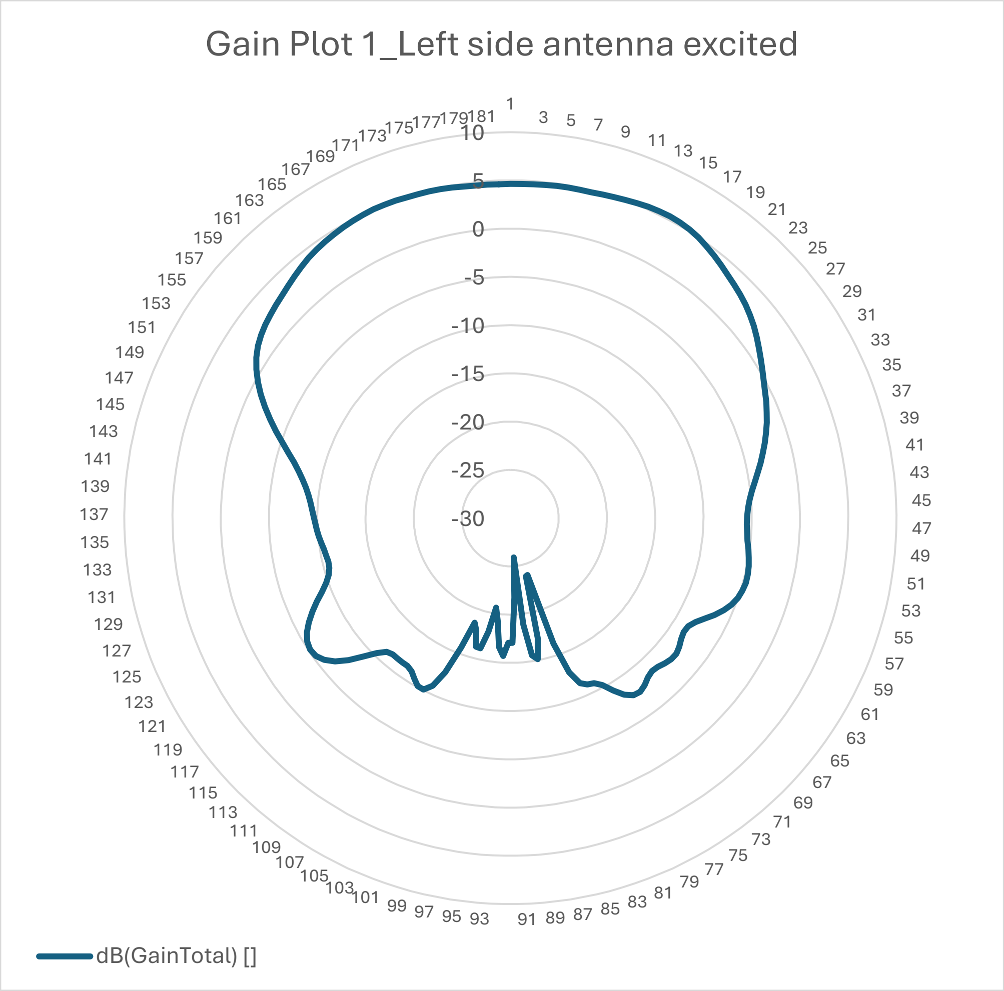


Figure 14. Gain plot when Single left side antenna excited. Zero tilt **gain 4.6dB** observed.

Case 4: Single Antenna on Top side Excited and other antenna off.

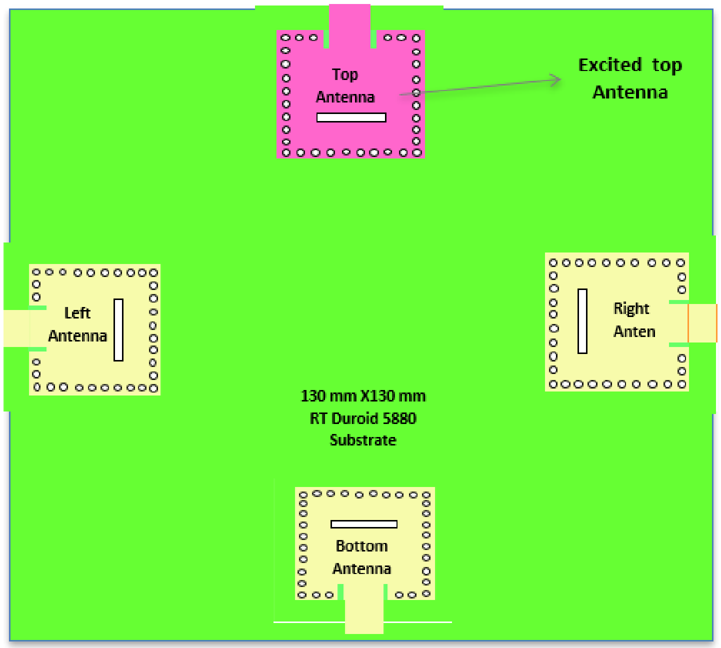


Figure 15. Single Antenna on TOP sidewall excited.

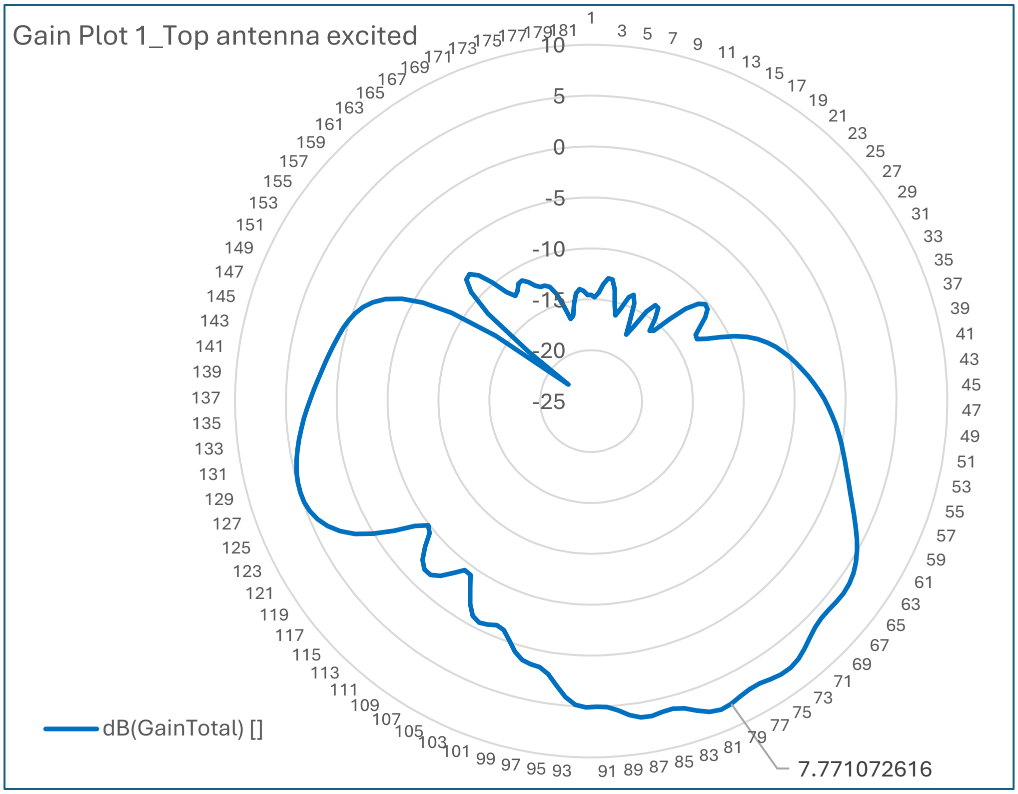


Figure 16. Gain plot when Single Top side antenna excited (-36^0 tilt gain 4.6dB). Gain = 73 ^{0} 5 dB and at -36^0= 7.77dB Bottom Right tilted Beam

Case 5: Two antennae Left and Right ones ON ie Excited without phase shift

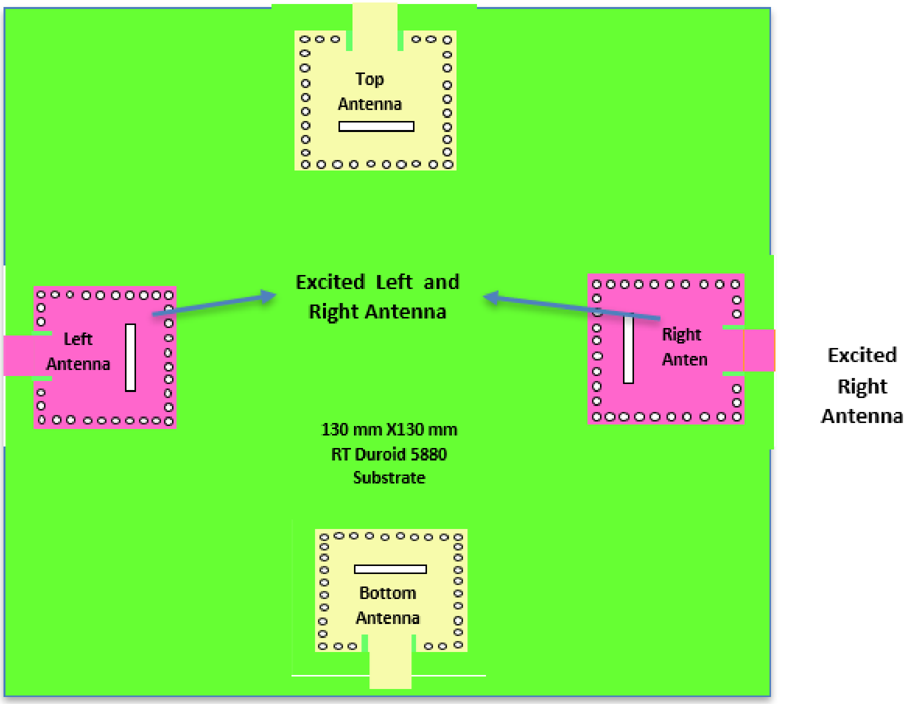


Figure 17. Two Antenna on sidewall Excited at a time.

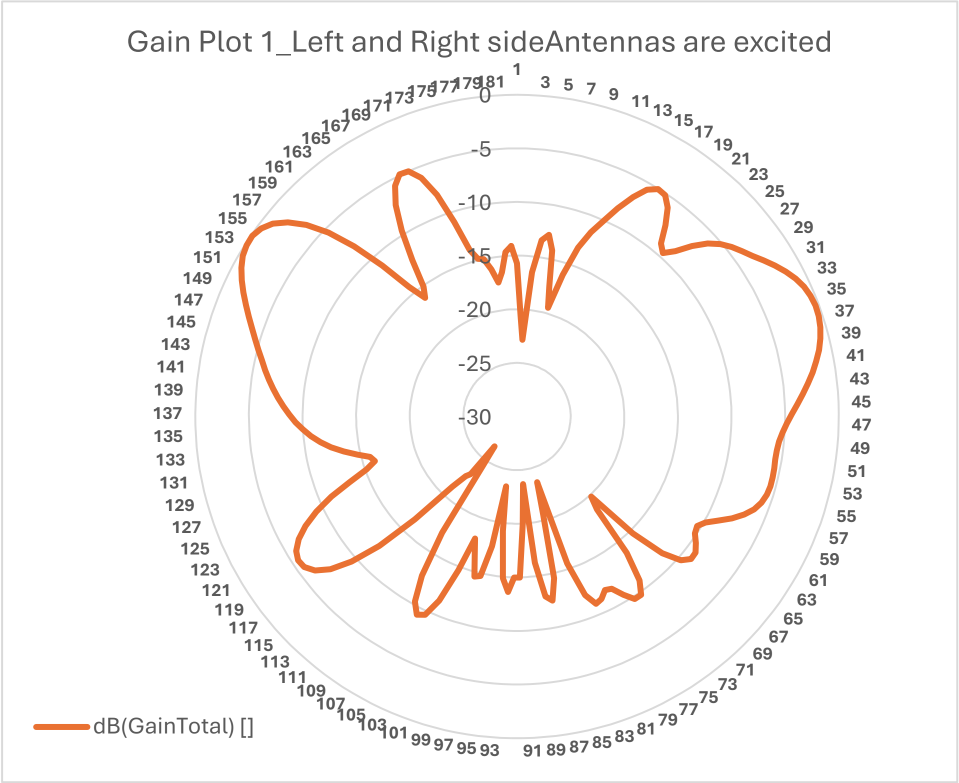


Figure 18. Gain plot when two side wall antennas are excited (Gain 7.7 db).

By increasing phase of port 3 from -60 to -150 degree, gain of main lobe increases gradually. This shows proper phase shift between two antennae help in diverting gain power to main lobe.

Case 6: Three Antenna Bottom + Side wall are ON ie Excited as shown in figure are axcited –

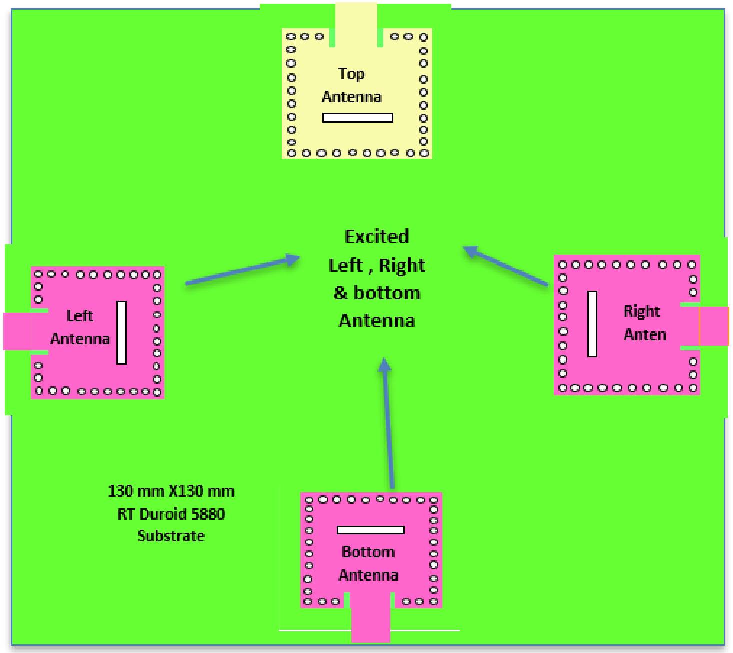


Figure 19. Three antennas, one on bottom and two side wall are excited.

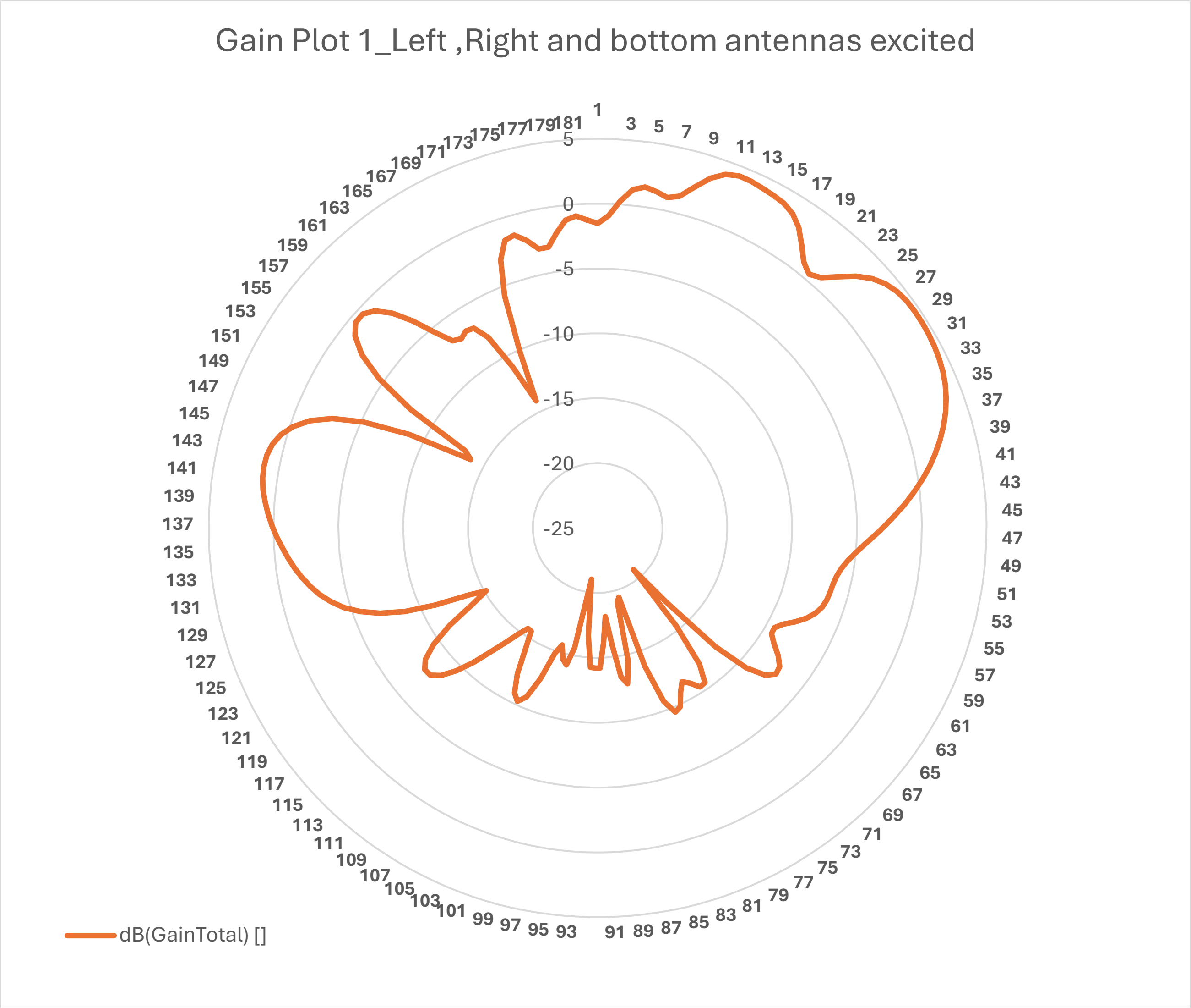


Figure 20. Gain plot when two side wall and one bottom antennas are excited.

Max Gain 4.4dB Top Right

Case 7: All Four Antenna ON: When all four antennas are excited with same signals without any phase shift, then omnidirectional radiation pattern is achieved with ripples as shown in figure 24.

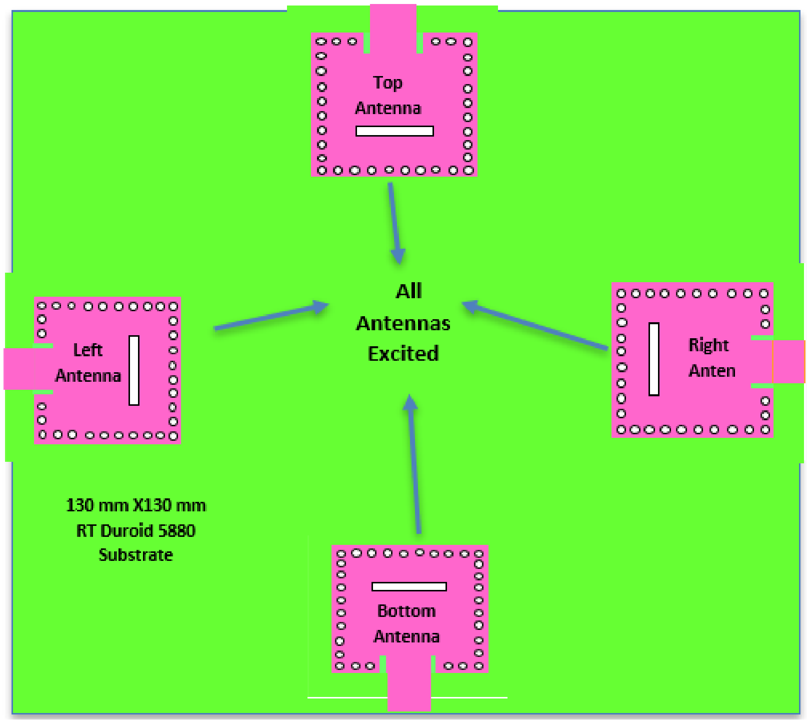


Figure 21. All four Antennas are excited.

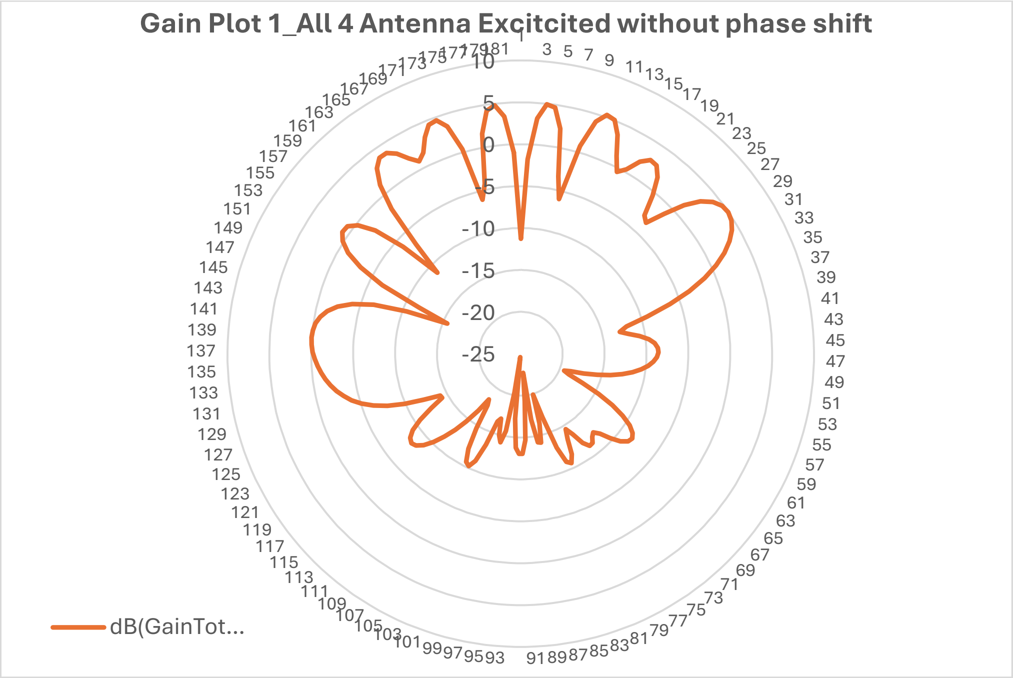


Figure 22. Gain plot when all four antennas are excited without phase shift.

This dynamic ON/OFF switching enables flexible beam reconfiguration without mechanical movement or complicated phase control circuits. The ripples can be removed with phase shift between 4 antenna signals.

V. Study of Radiation Pattern Ripples

Ripples in the radiation pattern are primarily attributed to phase mismatch and amplitude imbalance among the feeding ports. If the signals are not properly synchronized in phase, constructive and destructive interference results in pattern undulations.

Phase-only tuning while maintaining constant amplitude helps achieve constructive interference among all 4 antennas, thereby reducing ripples and enhancing gain in the desired direction. Amplitude tapering is employed to suppress sidelobes and further smoothen the radiation pattern.

Phase mismatch between the ports

If the signals feeding the 4 antennas are not perfectly in phase (or with proper phase differences), you get constructive and destructive interference at different angles → resulting in pattern ripples.

in below example only phase of antenna changes without changing amplitude. This helps in making constructing interference between all 4 antennae. By adjusting phase between the port, ripples can be minimized and hence can increase gain in desired direction. Below is one example of it.

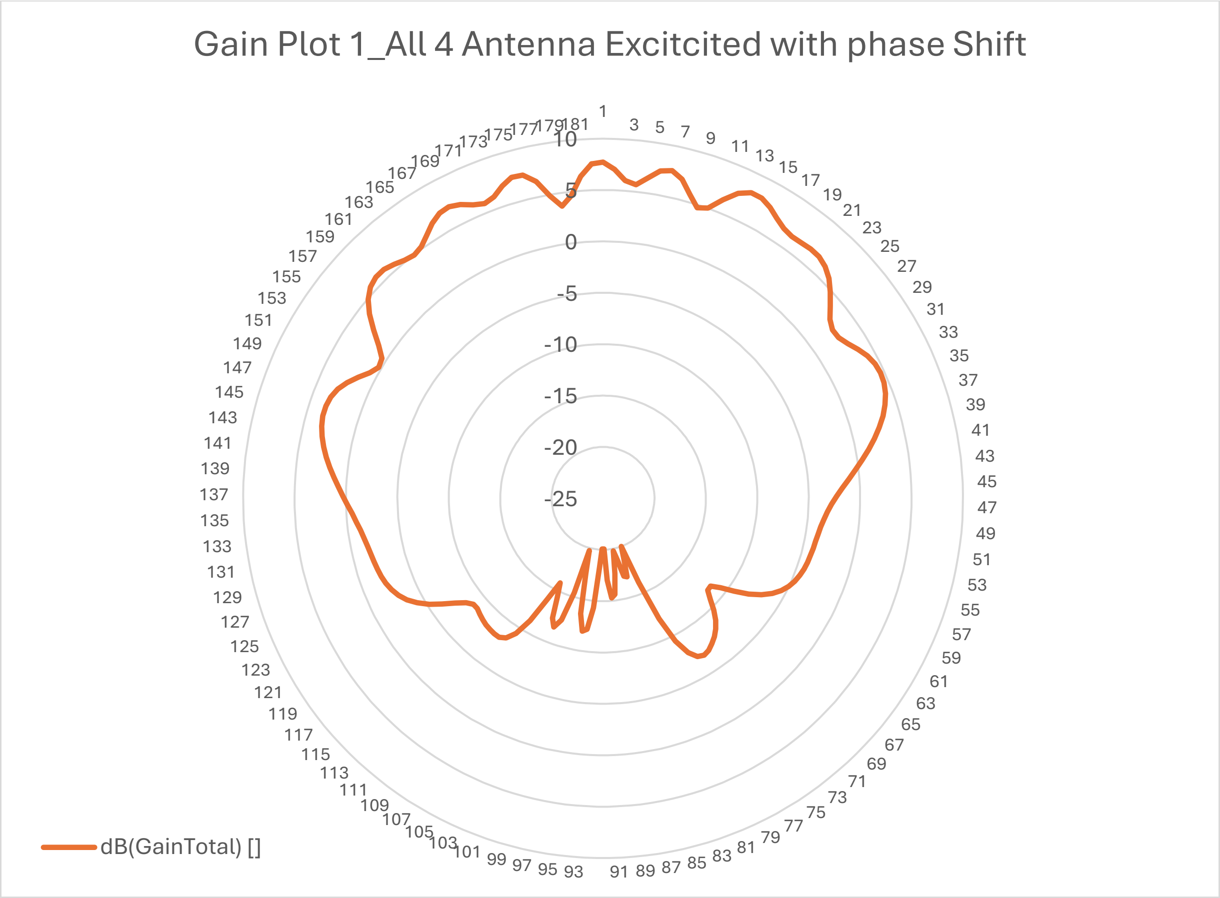

Gain Plot 1_All 4 Antenna Excitcited with phase Shift

Figure 23. Radiation pattern improvement using amplitude tapering.

Table 2. Effect of phase adjustment on radiation pattern ripples.

Source	Magnitude / Unit	Phase /Unit
Port 1	**2 W**	**120 deg**
Port 2	**2 W**	**-30 deg**
Port 3	**2 W**	**-150 deg**
Port 4	**2 W**	**30 deg**

Imperfect amplitude balance

If the feeding power to each antenna is not properly aligned, it can cause **amplitude imbalance**, leading to asymmetrical patterns with ripples. In below example amplitude in such a way that we will get minimum ripples.

This is also called **Amplitude tapering** which is one of the smart ways to **control** or **reduce** ripples caused by **imperfect amplitude balance** and **sidelobes**.

Key Features of the 4-SIW Cavity-Backed Antenna System:

Configuration:
Four SIW antennas placed on the four walls of a square cavity-backed patch.

Radiation Performance:
Half Power Beam width (HPBW): >100° (wider than conventional designs)
Gain: 7.7 dB (stable and moderate)
Good return loss:
S11, S22, S33, S44 >–15 dB.

Cavity-Backed Behavior:
Typically: Cavity-backed SIW antennas have high Q (narrowband) and narrow beam width.
In this design: Achieved bandwidth of 300MHz and wider beam width (~100°), enhancing angular coverage without sacrificing gain. High Front to Back ratio **- >30dB**

Mutual Coupling:
High port isolation: >30 dB between ports due to spatial diversity and cavity design.

Diversity Techniques:
Spatial diversity:Orthogonal placement of antennas improves signal decorrelation.

Beam Steering Capability:
Flexible beam steering by selectively turning ON/OFF different antennas without mechanical rotation.

Feeding Strategy

Earlier: ripples in gain and beam tilting.
Suggested: Progressive amplitude and phase feeding to further suppress ripples.

RESULTS AND DISCUSSION:
The proposed four-element SIW cavity-backed antenna system demonstrates the following key features:

1 Wide HPBW (>100°) with stable gain (~7.7 dB).
2 Good impedance matching with S {11}, S {22}, S {33}, and S {44} below –15 dB.
3 High front-to-back ratio (>30 dB).

4 Excellent port isolation (>30 dB) due to spatial diversity and cavity-backed design.

5 Flexible beam steering without mechanical movement or complex feeding networks.

Compared to conventional cavity-backed SIW antennas, which typically exhibit narrow bandwidth and beamwidth, the proposed design achieves a favorable balance between bandwidth, gain, and angular coverage.

2. CONCLUSION

A cavity-backed full-mode SIW antenna operating at 10 GHz has been successfully designed and analyzed. By scaling the design from millimeter-wave frequencies to the X-band, practical fabrication and measurement challenges are effectively addressed. The extension to a four-element antenna system demonstrates flexible beam steering through selective ON/OFF control and phase tuning. The proposed antenna platform offers wide bandwidth, high isolation, and reconfigurable radiation characteristics, making it a strong candidate for X-band communication, sensing, and radar systems.

References

1. D. Deslandes and K. Wu, “Integrated microstrip and rectangular waveguide in planar form,” IEEE Microwave Wireless Compon. Lett., vol. 11, no. 2, pp. 68–70, Feb. 2001.
2. Y. J. Cheng, W. Hong, and K. Wu, “Substrate integrated waveguide (SIW) antenna technology,” IEEE Antennas Propag. Mag., vol. 54, no. 5, pp. 25–40, Oct. 2012.
3. Author et al., “Design of Self-Duplexed Hybrid Substrate Integrated Waveguide Antenna for Sub-6 and mm-Wave Application,” SSRG Int. J. Electronics and Communication Engineering, vol. 11, no. 7, Jul. 2024.
4. Yan S., Soh P. J., “Dual-Band Textile MIMO Antenna Based on Substrate Integrated Waveguide (SIW) Technology”, IEEE Transactions on Antennas and Propagation, DOI 10.1109/TAP.2015.2477094.
5. Chaturvedi, D., Raghavan, S.: “A dual-band half-mode substrate integrated waveguide-based antenna for WLAN/WBAN applications”, Int. J. RF Microw. Comput. - Aided Eng., 2018, 28, (5), pp. 1–9.
6. Khan A., Geng S., Zhao X., Shah Z., Jan M. U., and Abdelbaky A. M., “Design of MIMO Antenna with an Enhanced Isolation Technique”, Electronics 2020, 9, 1217; doi:10.3390/electronics9081217.
7. Josephine A. C., Malathi and Thiripurasundari D. “Review on Isolation Techniques in MIMO Antenna Systems”, Indian Journal of Science and Technology, Vol 9(35), doi: 10.17485/IJST/2016/v9i35/96704.
8. Pramodini, B., Chaturvedi, D. and Rana, G., 2022. “Design and investigation of dual-band 2× 2 elements MIMO antenna-diplexer based on half-mode SIW.” IEEE Access, 10, pp.79272-79280.
9. A. Kumar, A. A. Althuwayb, and M. J. Al-Hasan, “Wideband triple resonance patch antenna for 5g WI-fi spectrum,” Prog. Electromagn. Res. Lett., vol. 93, pp. 89–97, 2020
10. Chaturvedi D., Kumar A., Raghavan S., “Wideband HMSIW-based slotted antenna for wireless fidelity application”, IET Microwaves, Antennas & Propagation, doi: 10.1049/iet-map.2018.5110.
11. Pramodini B., Chaturvedi D., “Miniaturized Inverted L-Shaped Slot Antenna Using HMSIW Technology”,
12. doi: 10.1109/PCEMS58491.2023.10136069. 1. A. Kumar and S. Raghavan, “A design of miniaturized half-mode SIW cavity backed antenna,” in 2016 IEEE Indian Antenna Week (IAW 2016), 2016
13. D. Chaturvedi, A. Kumar, A. A. Althuwayb, and F. Ahmadfard, “SIW- backed multiplexing slot antenna for multiple wireless system integration,” Electron. Lett., vol. 59, no. 11, 2023.
14. Chaturvedi, D. and Raghavan, S., 2017, November. A quarter-mode SIW based antenna for ISM band
15. application. In 2017 IEEE International Conference on Antenna Innovations & Modern Technologies for Ground, Aircraft and Satellite Applications (iAIM) (pp. 1-4). IEEE.
16. Design of Self-Duplexed Hybrid Substrate Integrated Waveguide Antenna for Sub-6 and Mm-Wave.