Performance Optimization of a Microstrip Patch Antenna using Characteristic Mode and D/Q Analysis

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Distribution A

OUTLINE

- Probe fed Rectangular Microstrip Patch Antenna
  - Conventional Design
  - Proposed Design
- Overview of Electrically Small Antennas
- Performance Comparison of Conventional and Proposed Design
- Characteristic Mode Analysis (CMA) of the Antenna
- Effect of Various Ground Plane Shapes on the Antenna Parameters
- Experimental Validation
- Antenna Optimization using D/Q Method
  - Calculation of Exact and Approximate Quality Factor
- Conclusion and Future Work

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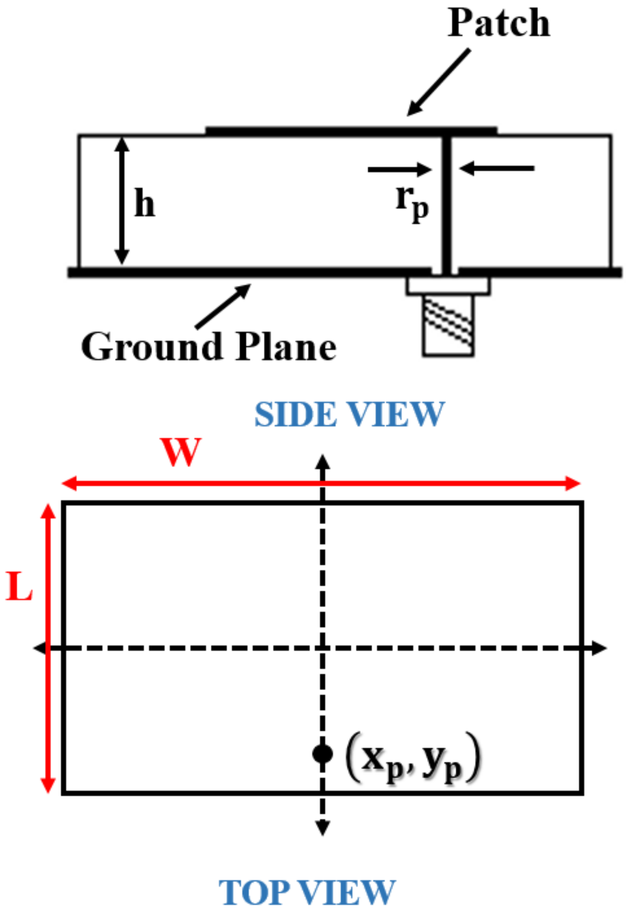
COAXIAL PROBE FED RECTANGULAR MICROSTRIP PATCH ANTENNA

- ❑ Microstrip patch antennas have found wide acceptance in the antenna community.
- ❑ Advantages: Light weight, Small size, Simple design, Tractable performance.
- ❑ Major disadvantage: Low VSWR bandwidth.
- ❑ Conventional Designs [1]: Coaxial probe is placed at an offset distance from patch center – Antenna I.
- ❑ The antenna dimensions are calculated using the equations in [2].

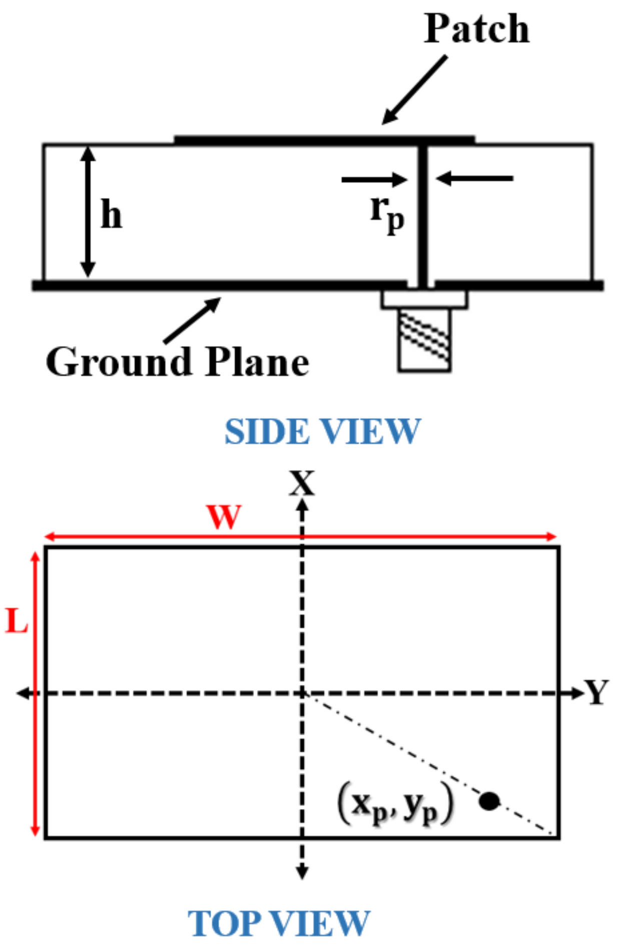


Antenna I

[1] R. Garg, P. Bhartia, I. Bahl, and A. Ittipibon, *Microstrip Antenna Design Handbook*, Boston, USA: Artech House, 2001.
[2] D. R. Jackson, *Introduction to Microstrip Patches*, IEEE International Symposium on Antennas and Propagation and USNC-URSI National Radio Science Meeting. Jul. 2013.

PROPOSED DESIGN – ANTENNA II

- Coaxial probe is strategically placed along the patch diagonal, at 2/3rd distance from the patch center.
- All other antenna dimensions are unchanged.
- > 30% 2:1 VSWR bandwidth could be obtained using this technique.



Antenna II

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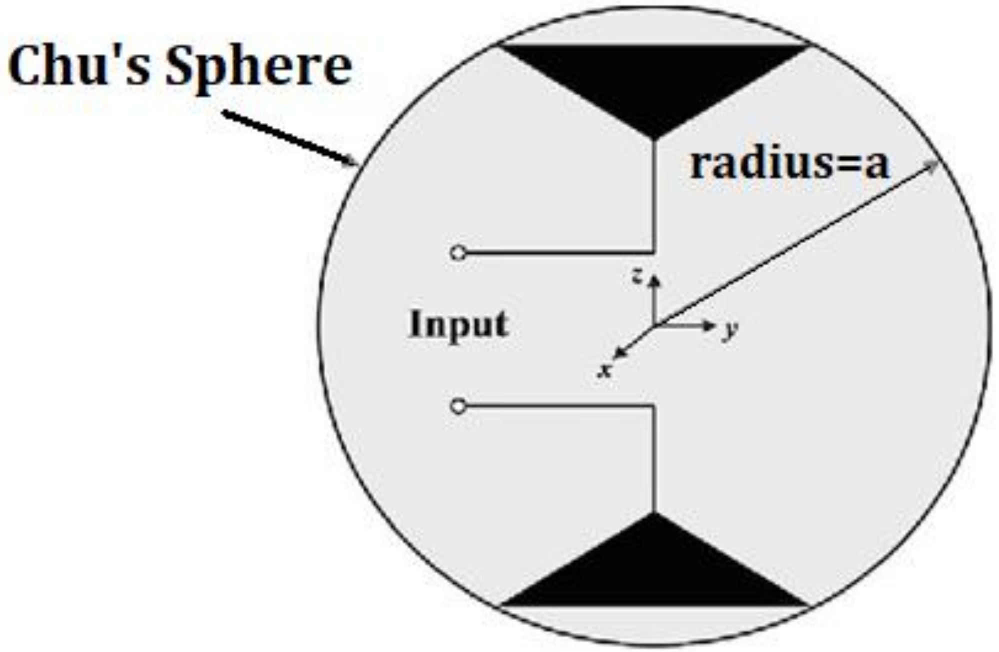
Overview of Electrically Small Antennas (ESAs)

Electrically Small Antenna (ESA)

Antennas that satisfy the condition $ka < 1$ where

$k = \frac{2\pi}{\lambda}$ is the wavenumber

a = minimum radius of the circumscribing sphere of antenna (Chu's Sphere)



[3] J. L. Volakis, C. C. Chen, and K. Fujimoto, *Small Antenna Miniaturization Techniques and Applications*. New York, NY, USA: McGraw-Hill, 2010.

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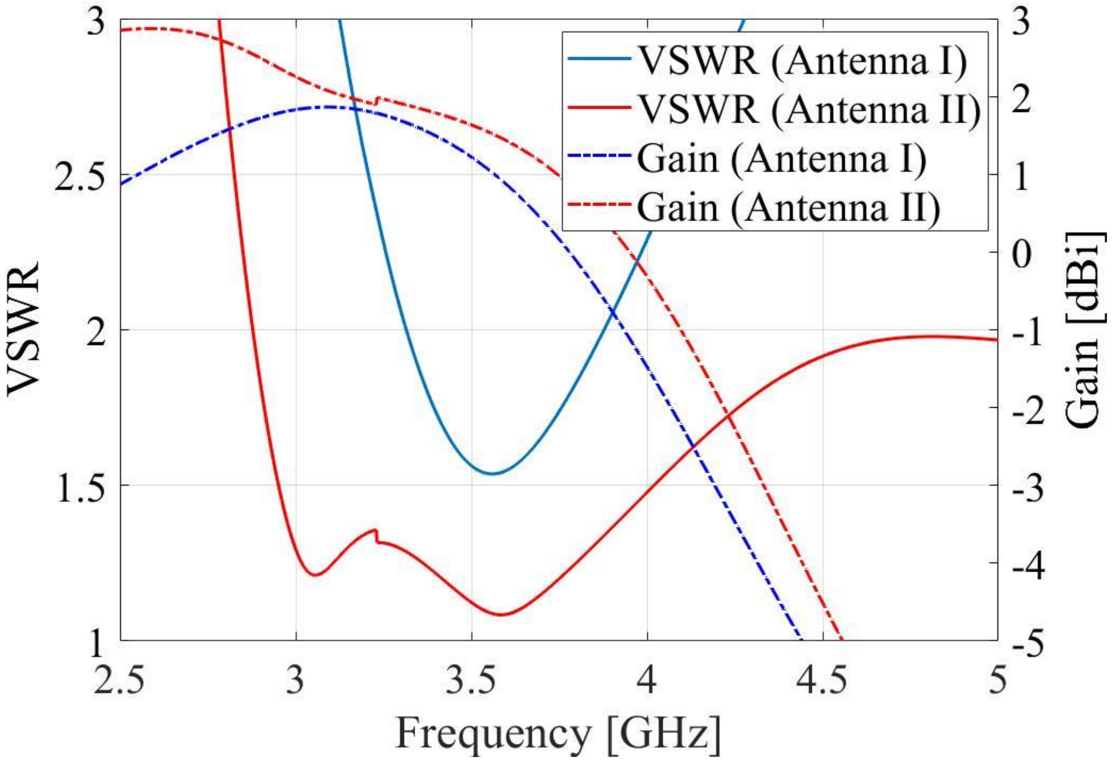
Performance Comparison of Antenna I and Antenna II

Parameters	Optimized Values
ε_r	9.8
tan δ	0.002
h (mm)	6.35
L (mm)	9.61
W (mm)	14.42
r_p (mm)	0.6



***Full-wave simulations have been performed using FEKO on an infinite ground plane.**

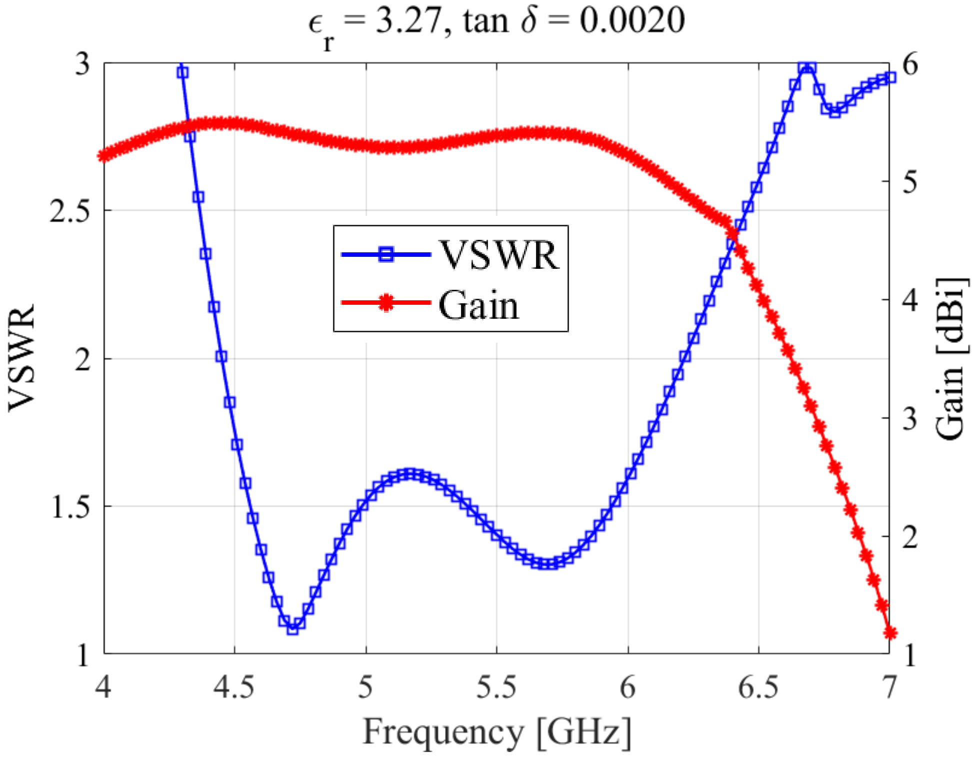
Antenna	(x_p, y_p) (mm, mm)	f_L (GHz)	f_c (GHz)	f_U (GHz)	% BW	Max. Gain (dB)	ka
ANTENNA I	(3.5, 0)	3.315	3.5975	3.88	15.70	1.86	0.6533
ANTENNA II	(3.2, 4.8)	2.867	3.6	4.333	40.72	2.85	0.6536

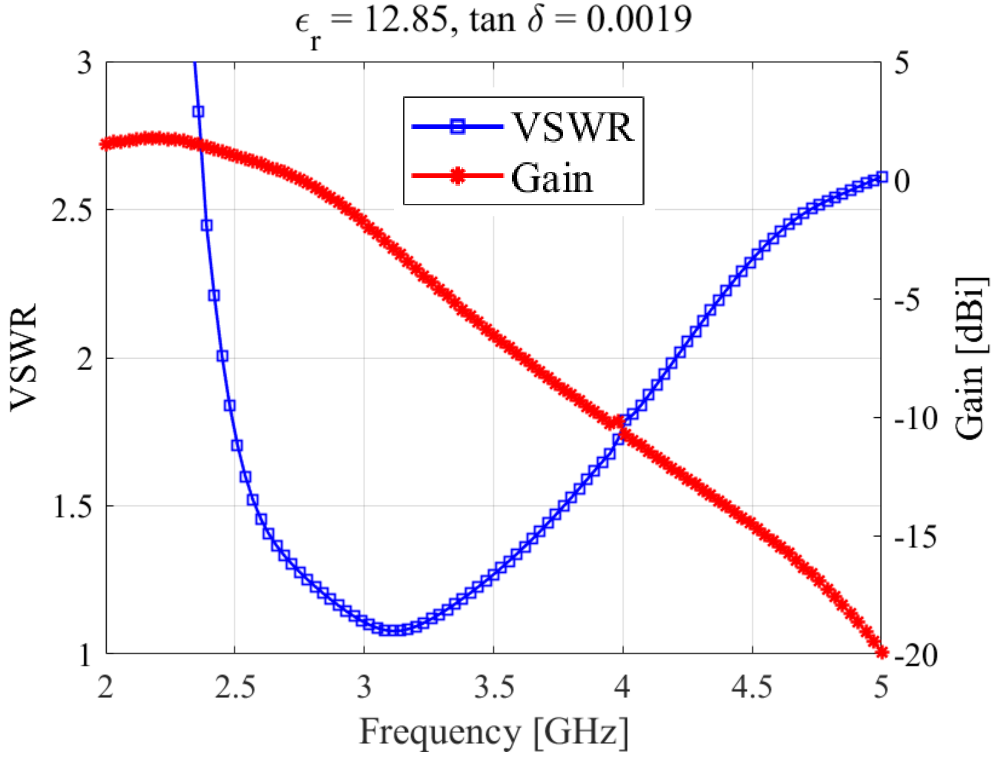
ESA (ka<1)

Design Methodology at Different Frequency Bands with Different Substrate Parameters

- This design methodology is applicable at all frequency ranges and for various substrate parameters.
- To prove this, we chose two other substrates (with different permittivity values):
  - $\varepsilon_r = 3.27$
  - $\varepsilon_r = 12.85$

Optimized Dimensions of the Antennas								
f_r (GHz)	ε_r	$\tan\delta$	h (mm)	$h\sqrt{\varepsilon_r}/\lambda$	L (mm)	W (mm)	r_p (mm)	(x_p, y_p)
5	3.27	0.0020	5.080	0.1532	11.4986	17.2478	0.9	(3.3, 5.7493)
2.5	12.85	0.0019	7.620	0.2278	9.1063	13.6594	0.6	(3.04, 4.55)





f_c (GHz)	% BW	Max. Gain (dB)	*ka*
5.35	33.86	5.49	1.16

f_c (GHz)	% BW	Max. Gain (dB)	*ka*
3.33	52.82	1.75	0.57

***Full-wave simulations have been performed using FEKO on an infinite ground plane.**

Conclusion: This design methodology yields > 30% 2:1 VSWR bandwidth irrespective of the frequency range and substrate parameters.

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CMA OF THE ANTENNA

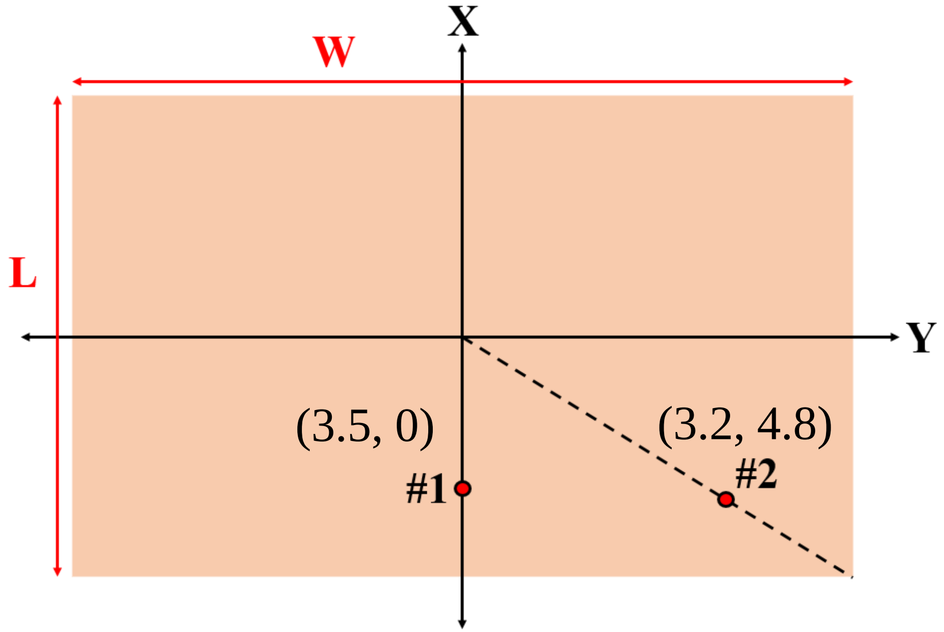
- The 2:1 VSWR bandwidth of the antenna has been found to be maximum when the probe is placed at 2/3rd distance along the patch diagonal.
- This may be attributed to the excitation of higher order modes.
- To identify contributing modes, CMA is performed for the antenna for the two probe locations.

- Modal behaviors of the antennas are illustrated via modal significance (MS_n) curves.
- MS_n shows the n^{th} eigen current mode:

$$MS_n = \frac{1}{|1 + j\lambda_n|}$$

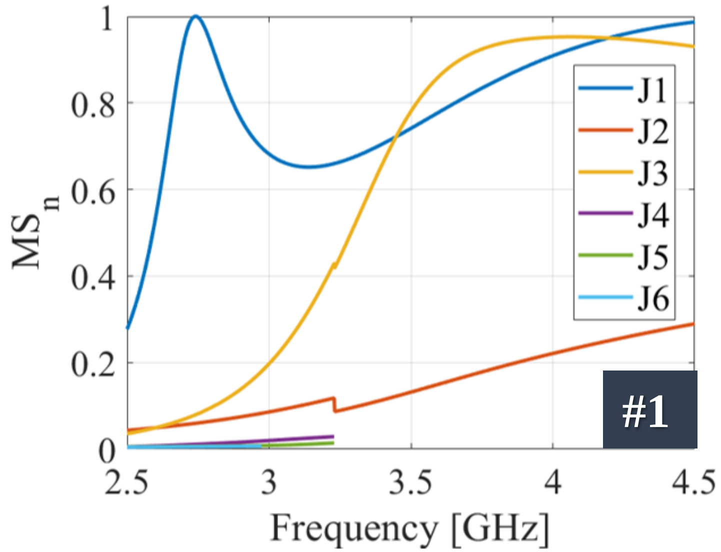
where, λ_n = eigenvalue for the n^{th} eigen current.

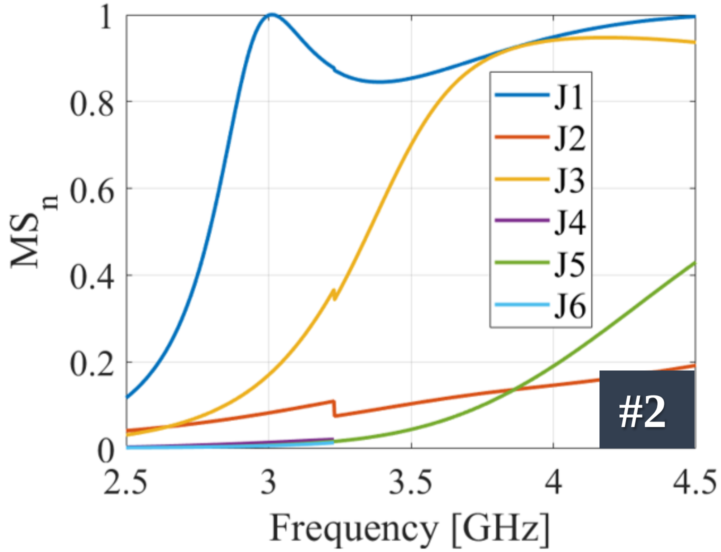
- n-th eigen current is considered dominant if its corresponding $\lambda_n = 0$ or $MS_n \rightarrow 1$ [4].

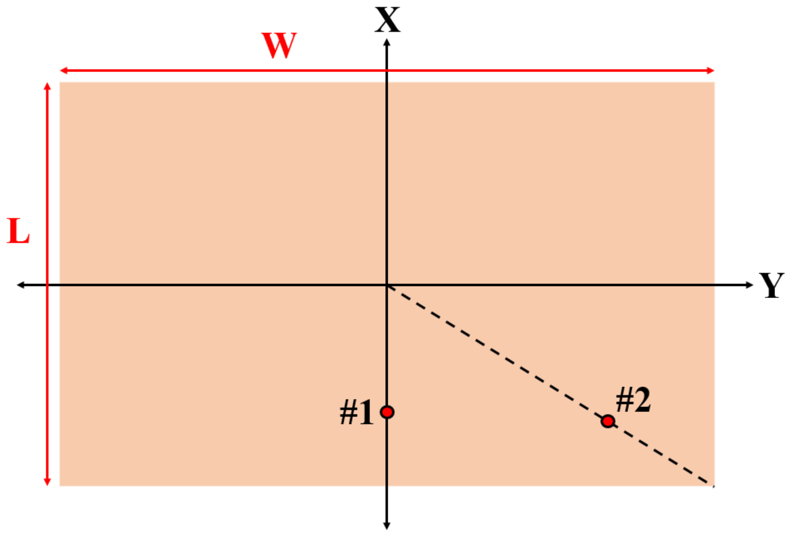


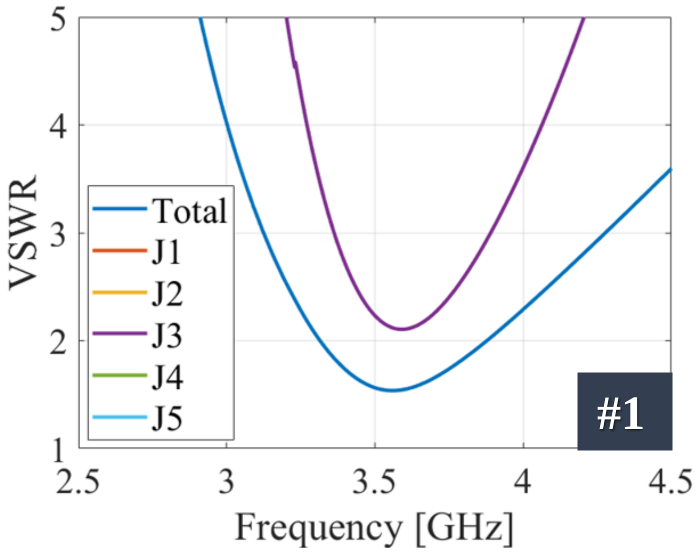
[4] M. Khan, and D. Chatterjee, "*Characteristic Mode Analysis of a Class of Empirical Design Techniques for Probe-Fed, U-Slot Microstrip Patch Antennas*," *IEEE Trans. Antennas and Propag.*, vol. 64, no. 7, pp. 2758-2770, July 2016.

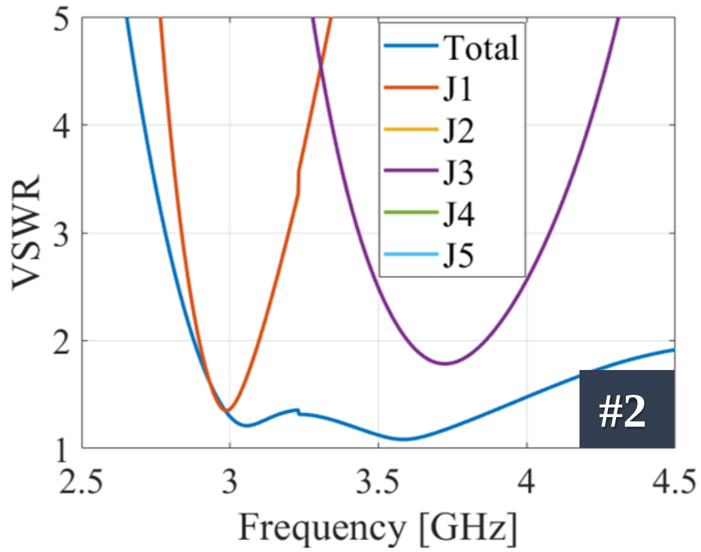
MS_n and VSWR of the Antenna for Different Probe Locations











Major contributing modes:
Position #1: Mode J3
Position #2: Modes J1 and J3

The bandwidth enhancement for #2 occurs due to excitation of multiple modes.

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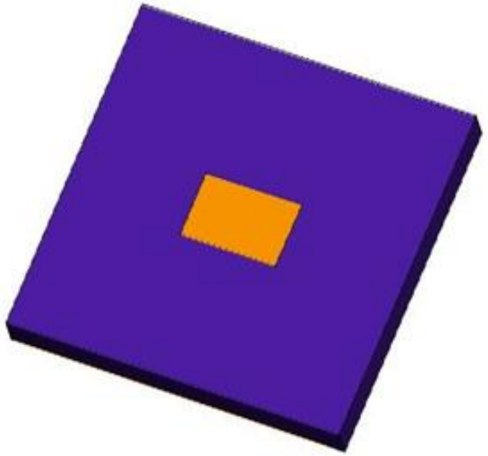
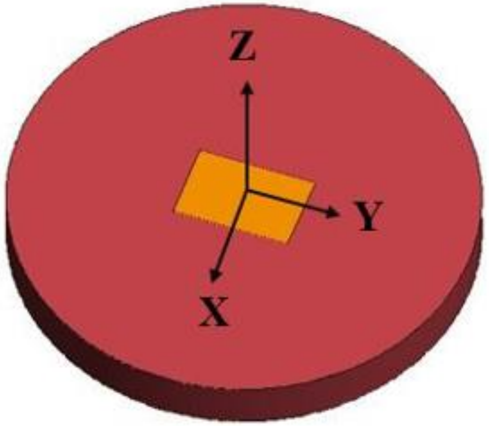
Effect of Ground Plane Shapes

- Experimental characterization of an antenna requires finite size PEC-backed substrate.
- To validate the design methodology, we chose the antenna design at 3.75 GHz on a TMM-10i substrate ($\epsilon_r = 9.8, \tan\delta = 0.0020$).
- Effect of finite ground plane on antenna parameters studied - Full-wave simulations performed via FEKO.
- Two different finite ground plane shapes are considered:
  - Square
  - Circular



Square Ground Plane

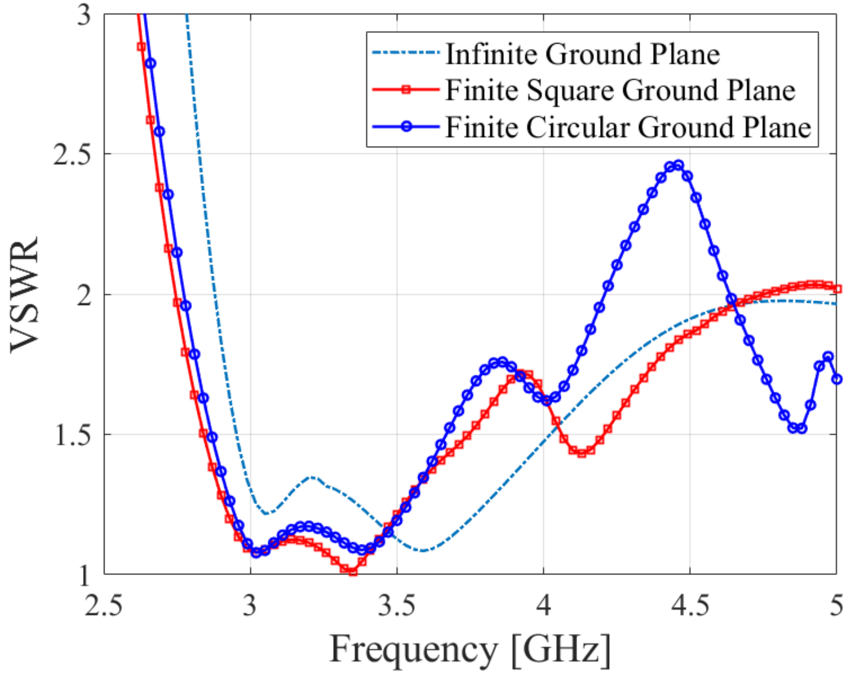


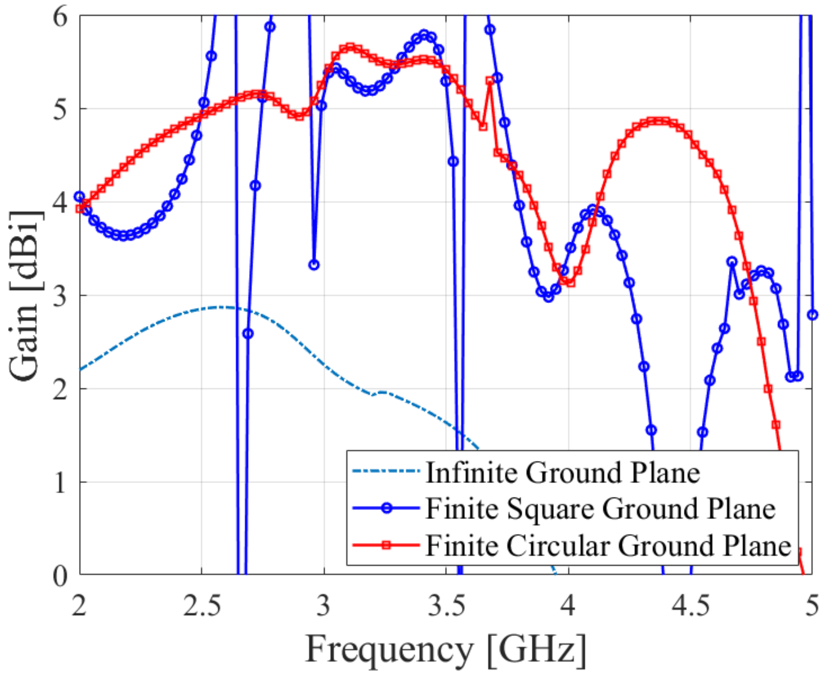
Circular Ground Plane

[5] Rogers Corporation.

SIMULATED RESULTS

Parameters	Optimized Values
ε_r	9.8
tan δ	0.0020
h (mm)	6.35
L (mm)	9.61
W (mm)	14.42
r_p (mm)	0.6
(x_p, y_p) (mm, mm)	(3.20, 4.80)





Ground Plane	f_L (GHz)	f_c (GHz)	f_U (GHz)	% BW	Max. Gain (dB)	ka
Infinite	2.867	3.6	4.333	40.72	2.85	0.6536
Finite Square (L_g = 41.64 mm)	2.773	3.491	4.209	41.13	unstable	0.6339
Finite Circular (r_g = 23.49 mm)	2.745	3.7475	4.75	53.50	5.65	0.6805

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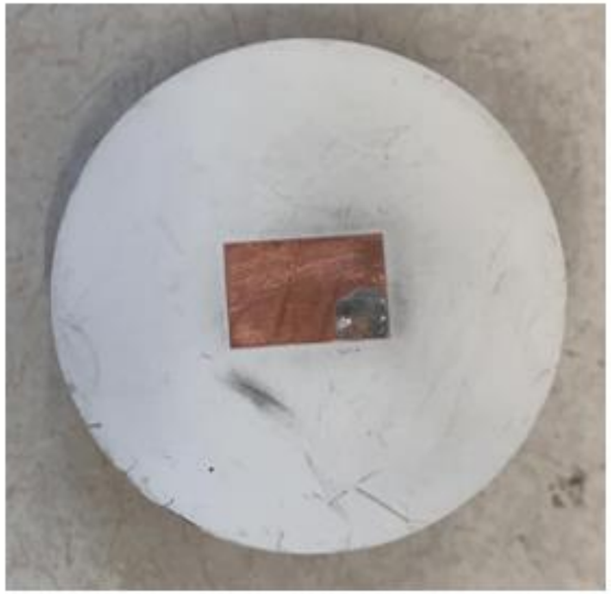
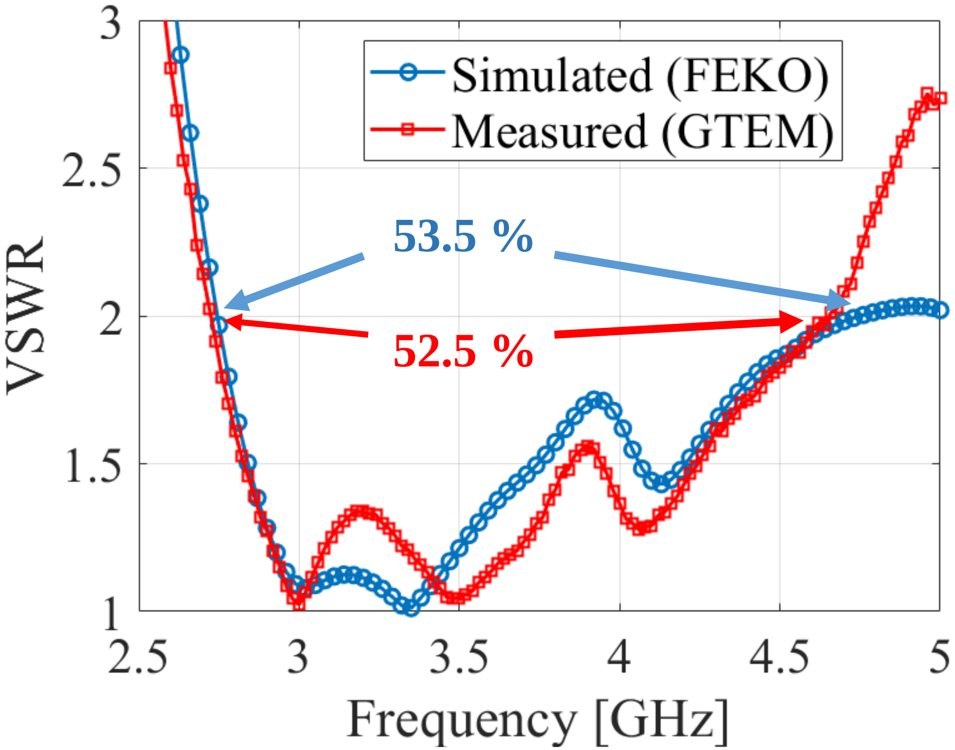
EXPERIMENTAL VALIDATION OF THE ANTENNA DESIGN

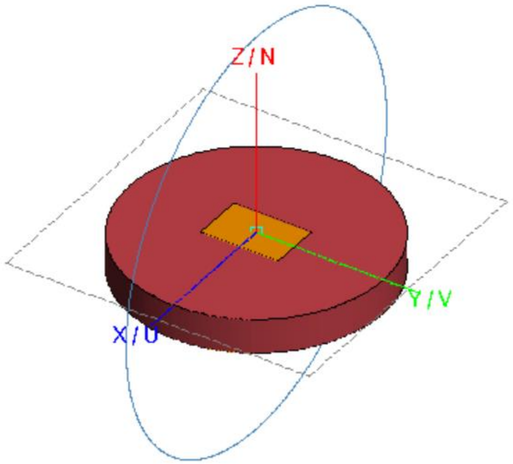


Fabricated Prototype

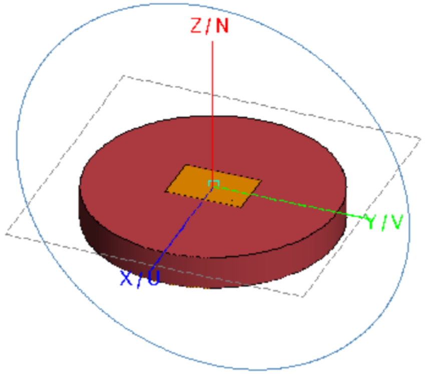


	f_L (GHz)	f_c (GHz)	f_U (GHz)	% BW	ka
Simulated	2.745	3.7475	4.75	53.50	0.6805
Measured	2.72	3.69	4.66	52.57	0.6701

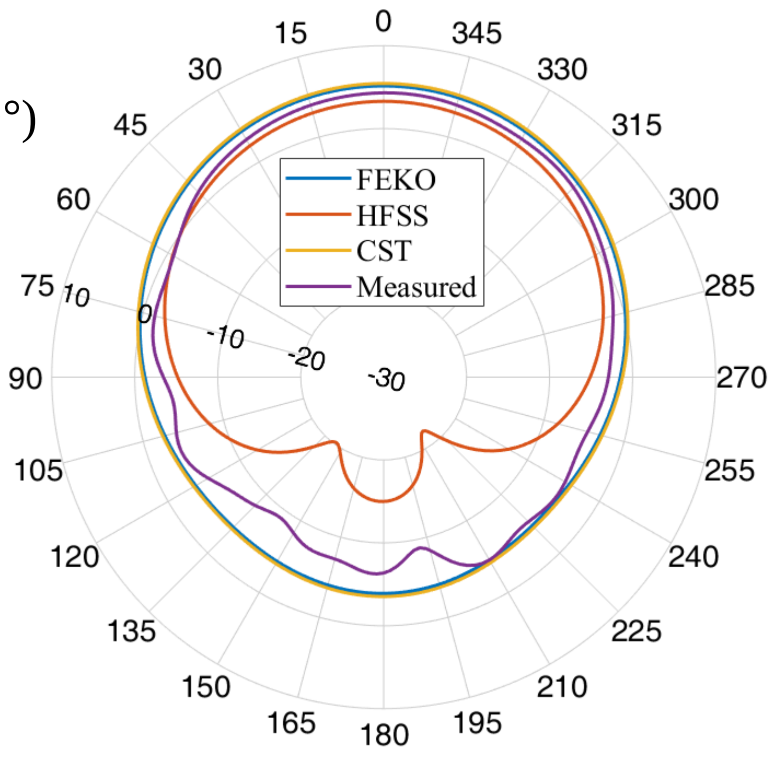
Radiation Pattern at Frequency = 2.745 GHz



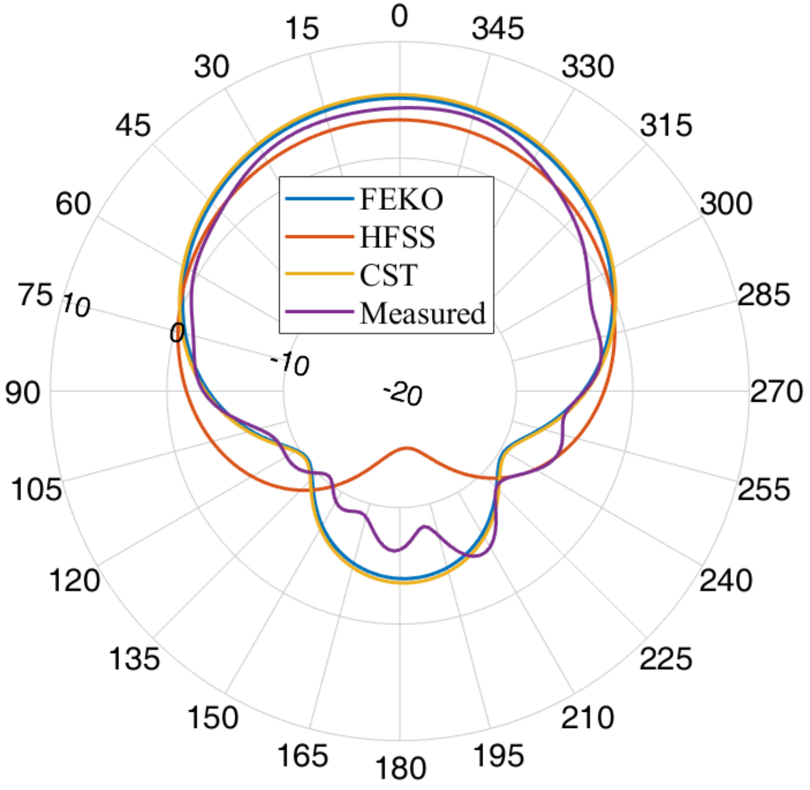
E-plane ($\phi = 0°$)



H-plane ($\phi = 90°$)

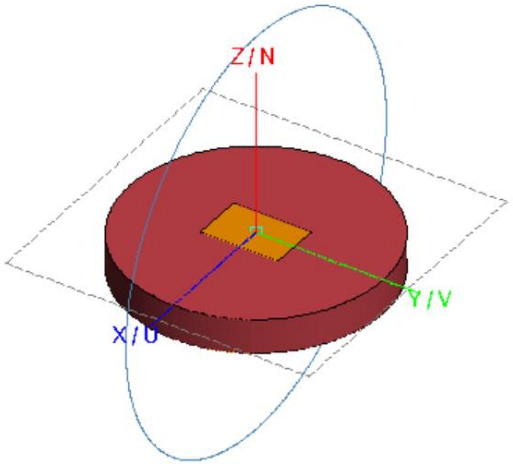


E-plane ($\phi = 0°$)

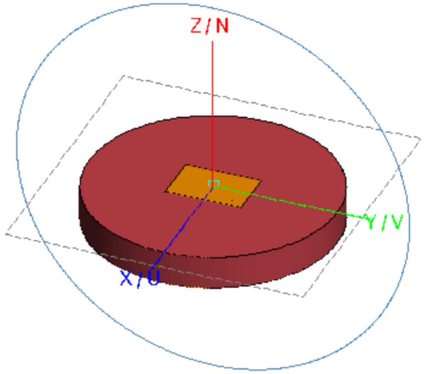


H-plane ($\phi = 90°$)

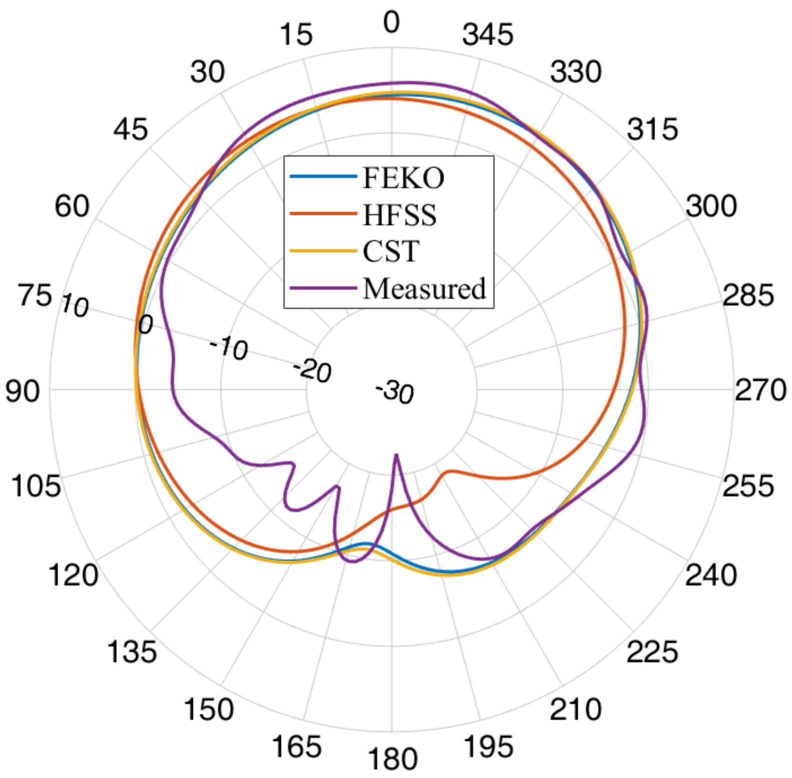
Radiation Pattern at Frequency = 3.7475 GHz



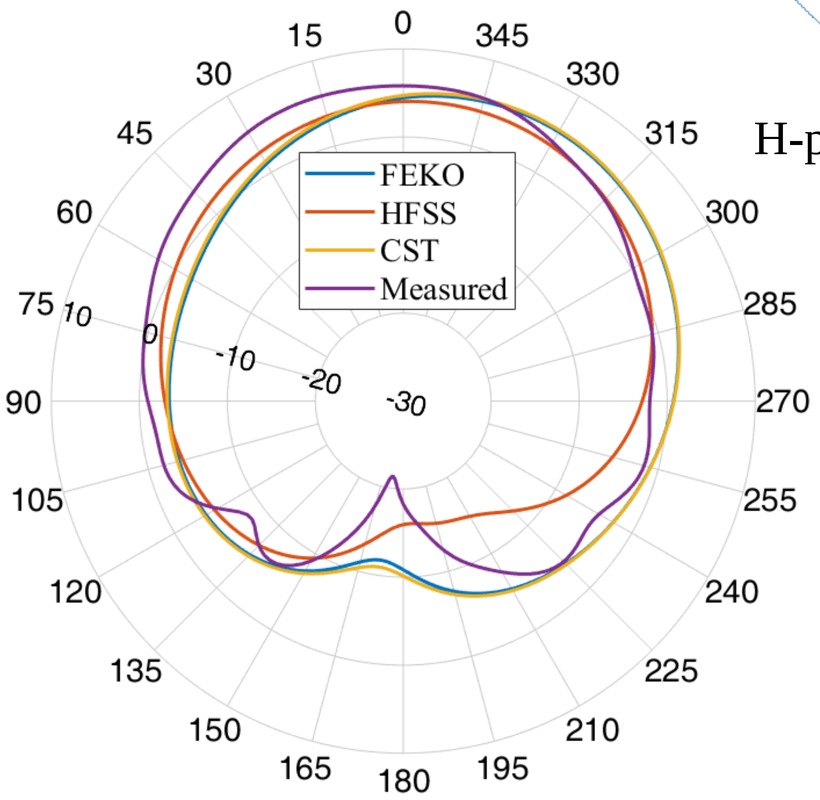
E-plane ($\phi = 0°$)



H-plane ($\phi = 90°$)

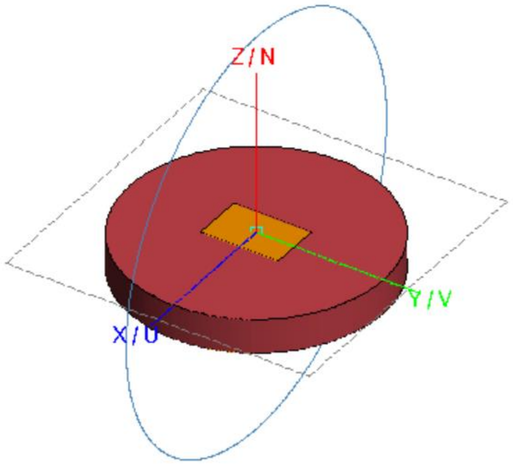


E-plane ($\phi = 0°$)

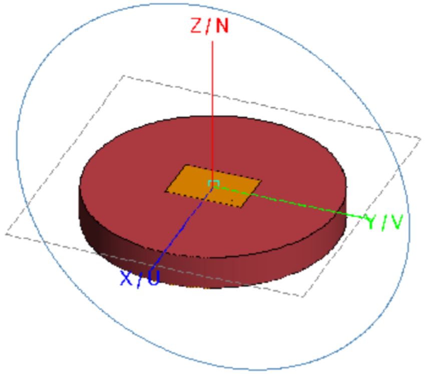


H-plane ($\phi = 90°$)

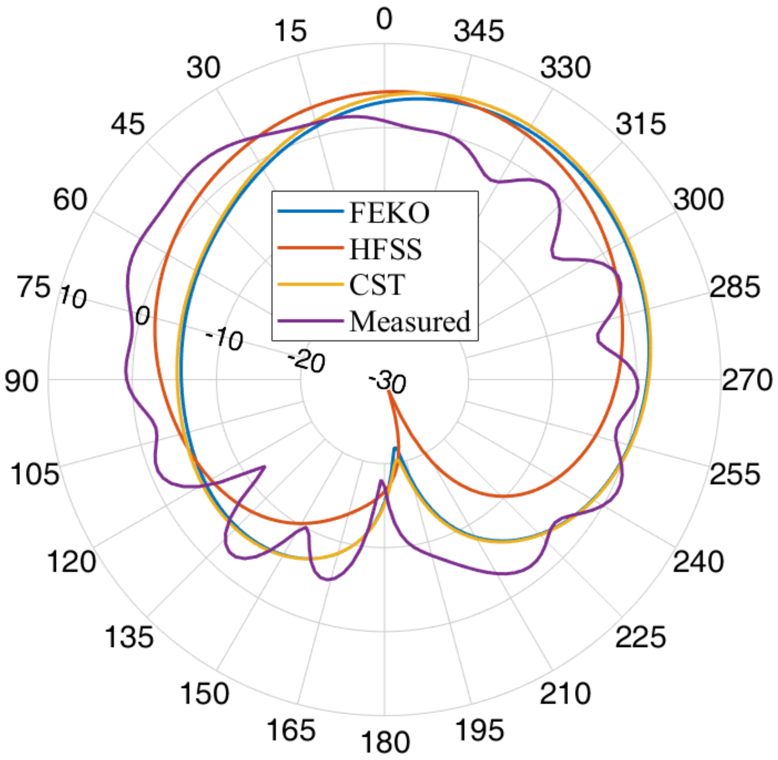
Radiation Pattern at Frequency = 4.75 GHz



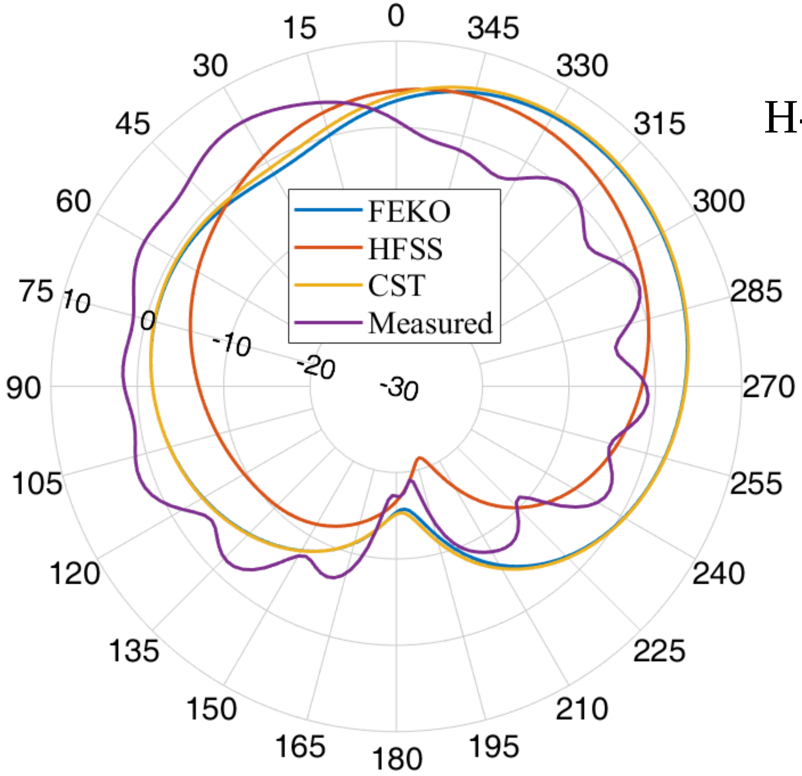
E-plane ($\phi = 0°$)



H-plane ($\phi = 90°$)



E-plane ($\phi = 0°$)



H-plane ($\phi = 90°$)

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D/Q OPTIMIZATION TECHNIQUE

- One of the useful performance optimization technique is the D/Q ratio of the antennas [6].
- D = Directivity (Far Field parameter)
- Q = Quality Factor (Near Field Parameter)
- Using this method it is possible to optimize the far field parameter and the near field parameter simultaneously.

- ❑ For our calculations, we exported the directivity from FEKO.
- ❑ Quality Factor of the antenna is calculated using two methods:

1. Exact Quality Factor (using antenna input impedance)
2. Approximate Quality Factors (applicable only for ESAs).

[6] M. Gustafsson, C. Sohl, and G. Kristensson, "Physical limitations on antennas of arbitrary shape," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 463, issue 2086, 2007, pp. 2589-2607.

Exact Q from Antenna Input Impedance [7]

$$Q(\omega_0) \approx \frac{2\sqrt{\beta}}{FBW_v(\omega_0)}$$

Where,

Matched VSWR Fractional Bandwidth

$$FBW_v(\omega_0) = \frac{\omega_- - \omega_+}{\omega_0}$$

And, $4\beta R_0(\omega_0) = \frac{X_0^2(\omega_\pm) + [R_0(\omega_\pm) - R_0(\omega_0)]^2}{R_0(\omega_\pm)}$

To calculate the exact Quality Factor, we are exporting the input impedance of the antenna from FEKO.

[7] A. D. Yaghjian and S. R. Best, "Impedance, Bandwidth, and Q of Antennas," *IEEE Trans Antennas and Propag.*, AP-53 , 4, April 2005, pp. 1298- 1324.

Approximate Quality Factors

- They take into account only the electrical length of the antenna (i.e., ka)
- Where, k = wavenumber and a = radius of the minimum sphere (Chu's sphere) that encloses the antenna.
- Since our designed antennas are electrically small, we consider these approximate expressions to check their validity for our design.

Harrington [8]:

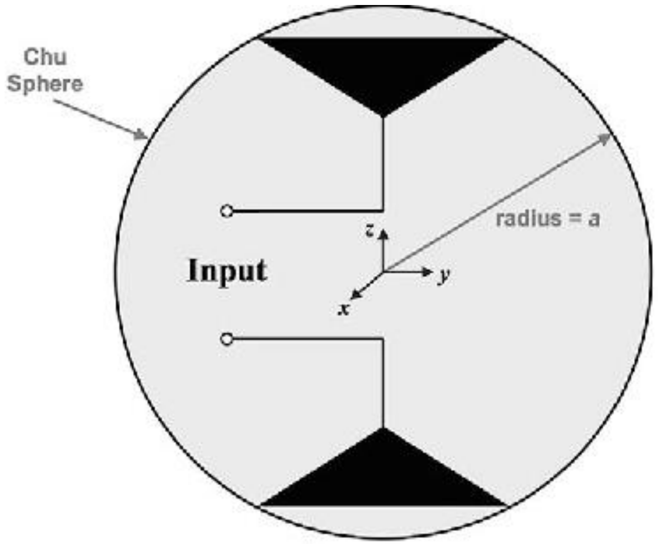
$$Q = \frac{1}{2}\left[\frac{1}{(ka)} + \frac{1}{(ka)^3}\right]$$

McLean [9]:

$$Q = \frac{1}{2}\left[\frac{2}{(ka)} + \frac{1}{(ka)^3}\right]$$

Thal [10]:

$$Q = \frac{1}{(ka)^3}$$



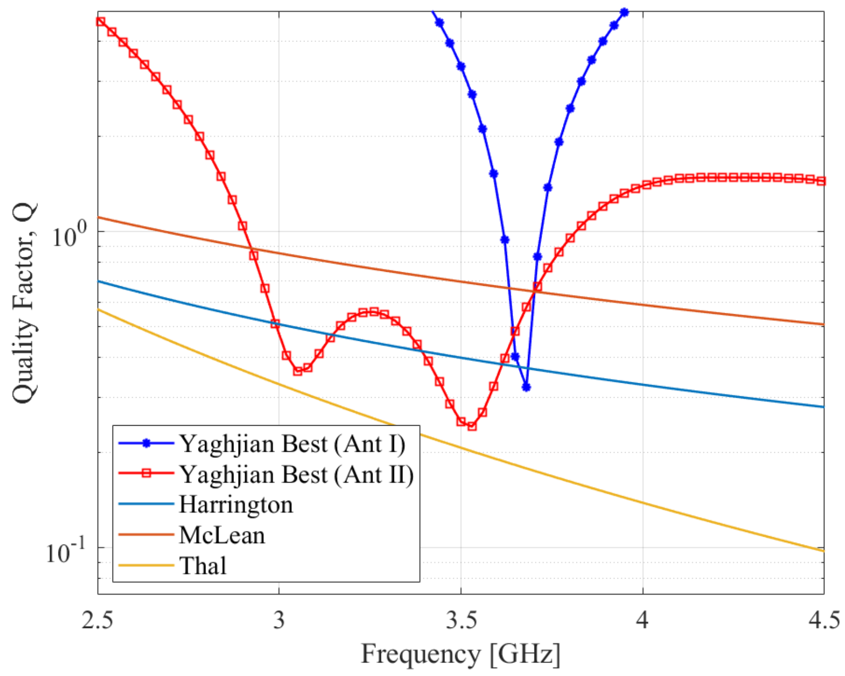
For ESA,
$ka < 1$

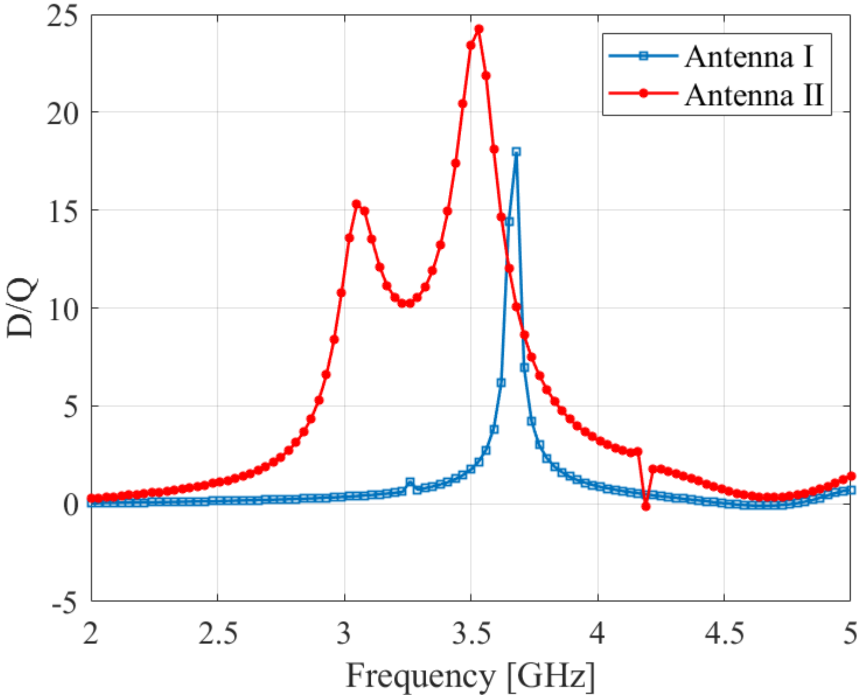
[8] R. F. Harrington, "Effect of antenna size on gain, bandwidth, and efficiency,“ *Journal of Research of the National Bureau of Standards*, vol. 64D, Jan. 1960, pp. 1-12.

[9] J. S. McLean, "A re-examination of the fundamental limits on the radiation Q of electrically small antennas," *IEEE Trans. Antennas and Propag.*, vol. AP-44, May 1996, pp. 672-675.

[10] H. L. Thal, "Gain and Q bounds for coupled TM-TE modes," *IEEE Trans. Antennas and Propag.*, vol. AP-57, no. 7, July 2009, pp. 1879-1885.

COMPARISON OF QUALITY FACTORS





D/Q RATIO VS. FREQUENCY

- Exact Q of the probe fed rectangular patch on finite circular ground is compared to the Approximate Quality Factors.
- For D/Q calculation, Directivity and Impedance exported from FEKO.

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CONCLUSION

- Presented a new method to obtain > 30% 2:1 VSWR bandwidth using a simple coaxial probe fed rectangular patch antenna – probe placed at 2/3rd distance along patch diagonal.
- Design methodology is experimentally verified.
- CMA shows increase in bandwidth is due to excitation of modes J1 and J3.
- Antennas designed on Circular Ground Planes have improved performances in terms of VSWR and Gain compared to Square Ground Planes.
- Optimization of antenna parameters using D/Q method has been explored.

FUTURE WORK

- Developing analytical model to characterize the designed microstrip patch antenna.
- Investigations into edge diffraction effects of finite ground planes.
- Investigations into the performance optimization of an antenna using the multi-parameter D/Q method.

Thank You