# Miniaturized MIMO Antenna with Complementary Split Ring Resonators Loaded Superstrate for X-band Application

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**Research Article**

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# Abstract

An aperture coupled two element metamaterial (MTM) antenna suitable for multiple input multiple output (MIMO) applications in the frequency band of 7.525-9.1GHz is proposed. This three-layered structure utilizes a vertical array of rectangular complementary split ring resonators (CSRR) between the contiguously placed circular non-bianisotropic complementary split ring resonator (NBCSRR) radiating elements for enhancement of isolation. This antenna achieves a maximum of 47dB isolation through this MNG structure insertion in the frequency band for 0.11 $\lambda_0$ separation of the two antenna elements. The proposed antenna achieves a fractional -10dB impedance bandwidth of 18.94% and has a peak gain of 8.15dB. The efficiency of the antenna is 84.14% and the envelope correlation coefficient is less than 0.03 in the operating band. The antenna is low profile with an overall size of 0.85 $\lambda_0$ x 0.45 $\lambda_0$ x 0.133 $\lambda_0$ and is suitable for X-band military applications.


# 1 | Introduction

MIMO antenna systems happen to be the vital cog of wireless communication system. The implementation of which currently has generated a plethora of issues to be sorted out by the researchers worldwide. One of the major issues in the development of multiple element antenna arrays for MIMO applications is mitigation of mutual coupling between the antenna elements that leads to severe degradation of system performance. This deleterious effect impacts antenna system parameters like bandwidth, gain, efficiency and impedance matching over the desired frequency range besides the radiation pattern and signal-to-interference-noise ratio (SINR). Since its vicious tentacles are spread over these crucial parameters, mutual coupling is the root cause of MIMO system performance degradation.

In multielement antennas, isolation enhancement is a major research problem that set off an extensive exploration of a variety of decoupling techniques. In the unsophisticated primitive techniques, miniaturization was the main casualty and the antenna systems became bulky and were not cost effective. Moreover, design complexity was an issue. MTM based antenna array systems are most suited for compact massive MIMO applications, since the compromise needed in the low-profile aspect of their design is almost negligible. While these exotic factitious materials revolutionized the realm of antenna design, isolation enhancement in MTM inspired multielement antennas useful in long term evolution (LTE) systems and array antennas for massive MIMO systems is a challenge currently confronting academicians and industrial scientists alike.

Mutual coupling in microstrip based and/or printed MTM antenna systems originates from surface wave propagation. Several novel decoupling techniques have been employed in MTM inspired antenna systems in the later years of current decade. Many innovative designs of multielement MTM antenna systems incorporating metasurface walls, electromagnetic bandgap (EBG) structures etc for decoupling the antenna elements have appeared in literature[2,3]. Since mutual coupling suppression down to the levels of -30dB is desirable which is a thumb rule in MIMO antenna system designs, scientists worldwide started their journey in quest of directions for optimizing MIMO communication systems through enhanced isolation of array elements which constitute the array antenna. Measurements on prototypes of designs achieving mutual coupling suppression even down to less than − 46.5dB levels have been reported in the literature[4]. The impact of MTM on antenna system designs is phenomenal[5–8]. Likewise, it offers many avenues to address a specific issue while designing an efficient multielement antenna system.

A class of MTM structures known as Electromagnetic bandgap structures or metasurface corrugations exhibit stop band and pass band characteristics for surface wave propagation. This property of EBG structures has been successfully utilized for attenuation of surface waves. Isolation and bandwidth enhancement have been achieved through two layer tunable EBG structures in unison with slit patch arrays placed between two monopole antennas[3,9]. Two closely spaced meander line antennas are effectively decoupled through an MTM substrate and this antenna system is reported to achieve an isolation of 12-19dB over 5.1-5.9GHz frequency band[2]. This simple design offers improved impedance matching and gain. Unwanted

frequency bands are notched for reducing multipath fading effects in four element UWB MIMO antenna system[17] and envelope correlation coefficient (ECC) of less than 0.02 is maintained across the operating frequency band [18].

An MTM mushroom wall has been used to improve isolation in a four element MIMO antenna system[10]. In this design, a crossed double layer mushroom wall structure integrated with substrate- integrated cavity-backed slot antenna elements and this system was shown to achieve an isolation of 42dB with an envelope correlation coefficient well below 0.02 within the operational band of 2.39-2.45GHz. In this design the height of the antenna system is rather high, limiting its use in MIMO applications. An array antenna decoupling surface (ADS) consisting of a thin substrate with flowery patterns of metal patches was tried out to suppress mutual coupling in a 4-element antenna and was found to bring down the mutual coupling to -30dB level[11]. Here the unwanted coupled waves are cancelled by controlling the partially diffracted waves from the ADS through carefully designing the metallic patch patterns. Though this method is promising, its usefulness is limited and it can be applied only for 2 x 2 arrays. As the number of elements in an array antenna increases, the patch patterns on the ADS become very complicated[1].

A Jerusalem Cross (JC) MTM unit cells based thin planar lens MIMO antenna system with seven elements was constructed and demonstrated to achieve mutual coupling levels lower than − 30dB which satisfies the threshold level desired by MIMO system requirement. However, compactness of the system suffers due to the large distance between the metalens and the element feeds and it is an issue that needs to be optimized for its suitability in MIMO communication systems[12]. Mutual coupling reduction in Dielectric Resonator antennas useful for 60GHz MIMO system has been attained through a metasurface shield[4]. The constructed prototype achieved mutual coupling levels of -30 to -46.5dB in the 59.3–64.8GHz frequency band.

A MIMO antenna system employing a frequency selective surface (FSS) wall has been reported to achieve − 30dB isolation levels[13]. The FSS walls of this system were optimized for the operating band of 57-63GHz to achieve this level which is a thumb-rule requirement in a MIMO system[1]. Envelope correlation coefficient (ECC) is an important parameter while analysing the diversity performance characteristics of a MIMO antenna system. This system has reportedly achieved an ultra-low ECC of $5x10^{-6}$ making this system appropriate to MIMO applications in this frequency band. FSS is an attractive candidate for mitigation of mutual coupling because of the flexibility it provides as far as the operating band is concerned. Yet another system operating in the frequency band of 30GHz employing crossed-dipole structures on the FSS has been reported[14] and it is very clear from the results of the investigations, varying degrees of isolation enhancement are achievable through optimization of the FSS for operation in a frequency band of interest. The air gap technique[19] is implemented in aperture coupled antenna design to improve the gain.

Recently surface wave attenuation in a patch array antenna was accomplished using a capacitively loaded loop metamaterial (CLL-MTM) superstrate and more than 55dB isolation was achieved at a centre frequency of 3.3GHz. This CLL-MTM will be very much useful in LTE communication systems as it can be used to improve the isolation of array antennas already in use, eliminating the necessity of replacing them with new ones[15]. A self-diplexing MIMO antenna improving the isolation has been reported[20,21]. In this paper a dual element antenna system is proposed for MIMO applications in the frequency band of 7.525-9.1GHz. To reduce the mutual coupling an MTM array is inserted in between two CSRR radiating elements. The radiating elements are stimulated through aperture coupling technique to increase the gain.

## 2 | Antenna Design

The proposed MIMO antenna design involves five stages from antenna A to antenna E. Single circular patch antenna A and MTM loaded antenna B are presented in Fig. 1. Though there exists a variety of options to load the MTM structure, aperture coupled MTM antenna loaded with air gap between two substrates is implemented to achieve high gain with bandwidth

enhancement. The first stage of the antenna is designed with a single circular patch. In the second stage, the famous circular NBCSRR printed as a radiating element on the upper surface of the substrate. In both cases, FR4-epoxy with a dielectric constant $\varepsilon_r$ of 4.4 with a dielectric loss tanδ = 0.002 is used. The aperture is made in the ground layer on the top of the bottom substrate and the feed line is provided in the bottom surface of the lower substrate of antenna B and the radiating element is printed on the top surface of the upper substrate as depicted in Fig. 2.

# 2.1 | Schematic of aperture coupling

Depicted in Figure.3 is a comprehensive picture of the aperture coupling realized in the present design of an all MTM MIMO. The feedline is printed on the bottom surface of the lower substrate. Meanwhile the ground plane is printed on the top surface of this substrate. Carved out of the same is an aperture of dimension 8mm x 1.3mm directly below the radiating element of each antenna. The radiating elements of the antennas are printed on the upper surface of the other substrate viz. the top substrate

# 2.2 | The proposed Design

The optimized values of the geometrical dimensions of the antenna are given in Table 1. The overall size of the antenna is 30mm × 16mm × 4.7mm. The antenna is excited through the bottom edge of the microstrip line and is powered up through an SMA connecter. As shown in Fig. 4, in antenna C and D an additional antenna element is printed to realize the MIMO antenna design.

Table 1
Dimensions of the proposed antenna

| Parameter | Dimension (mm) | Parameter | Dimension (mm) |
|---|---|---|---|
| L | 16 | $S_w$ | 1.3 |
| W | 16 | S | 4 |
| $L_s$ | 10 | $r_1$ | 4.9 |
| $W_s$ | 2 | $r_2$ | 4 |
| $S_l$ | 8 | $r_3$ | 2.5 |
| $L_a$ | 16 | g | 0.8 |
| $W_a$ | 30 | $S_1$ | 0.8 |
| D | 8.9 | d | 4 |
| $W_a$ | 30 | h | 1.5 |

Two NBCSRR elements of outer ring radii $r_1$ = 4.9mm with a distance of separation of the order of $\lambda_0/8.3$(4mm) are printed on the superstrate of FR4 -epoxy with lateral dimensions $L_a$= 16mm, $W_a$= 30mm and thickness 1.6mm. The dimensions of the substrate containing ground, aperture ($S_w$ x $S_l$ = 1.3mm x 8mm) and the microstrip feedlines ($W_s$ = 2mm) are also the same.

An air gap of around 1.5mm has been maintained between the superstrate and the substrate to achieve a gain of 8.15dB at the resonant frequency of 8.5GHz.

Though the MTM radiating elements loaded in antenna D are self diplexing, mutual coupling is greatly reduced only after inserting the rectangular vertical MTM array in between the two radiating elements as shown in Fig. 5 and all the

characteristics of the antenna are simulated through finite element based HFSS, an Ansys software.

## 3 | Parametric Analysis

The primary goal of the present antenna design is isolation between the radiating elements. Keeping this in mind, the air gap h, the stub length S and the aperture length $S_l$ are given importance in this analysis.

# 3.1 | Air gap optimization

Figure 6 shows that the resonant frequency shifted in the direction of positive x values as the air gap height h value increases from zero. At the value of 1.5mm of h, the antenna achieves a gain of 8.15dB as depicted in Fig. 12(a) with a bandwidth of about 1.575GHz. This prompted us to decide upon the optimized value of h = 1.5mm.

# 3.2 | Stub length S optimization.

The stub length is one of the main components to effect improvement in the return loss. Stub length S improves the return loss about − 40dB in its 4mm value at the resonant frequency of 8.5GHz while effecting insignificant variation in its other values, viz. 3mm, 3.5mm, 4.5mm and 5mm, as depicted in Fig. 7. Hence the optimized stub length value has been taken as S = 4mm.

# 3.3 | Aperture length $S_l$ optimization

Aperture length $S_1$ is one of the major elements in this type of antenna to stimulate the radiating element. The aperture length is properly chosen to resonate the antenna over the desired band of frequency. Hence, the aperture length $S_1$ is optimized at the value of 8mm in the resonant frequency of 8.5GHz with a return loss of -40dB which has been delineated in Fig. 8.

# 3.4 | Antenna fabrication

After the optimization of the parameters, an antenna prototype has been fabricated which is shown in Fig. 9.

## 4 | Results And Discussion

To ascertain the impact of the non-bianisotropic nature of the MTM unit cell on bandwidth enhancement, return loss simulation was carried out on the fabricated prototype loaded with a simple CSRR also and the results are presented in Fig. 10. The proposed MIMO antenna is resonating at 8.5GHz (useful in X band wireless applications). It is to be noted that unlike the many MTM antennas reported in the literature, the proposed antenna exceptionally achieves a wide fractional − 10dB impedance bandwidth of 18.94% in the frequency range of 7.525GHz – 9.1GHz.

The measured and simulated S-parameters of the antennas are presented in Fig. 11. ENA series E5071C Vector Network Analyser (VNA) was employed in the S-parameter measurements on the prototype. Good agreement between the measured and simulated values is distinctive from the curves. The slight discrepancy in the return loss curves could be due to the fabrication tolerance and the parasitic arising out of the soldering. From the curves, it is concluded that the isolation is maintained up to 47dB in between the measured values of $S_{11}$ and $S_{21}$ in the operating frequency band.

Figure 12 (a) shows that the gain is gradually increasing when the air gap value increases from zero to1.5mm. At zero-air gap, a gain of 3dB is maintained through the bandwidth. It has been increased up to 8.15dB when the air gap is kept at 1.5mm. It has to be noted that air gap variation is possible only if the antenna is designed with aperture coupling.

Additionally, efficiency of the antenna is also increased from 50–81.14% when the air gap is varied from 0 to 1.5mm. Iteration of antenna gain and efficiency are depicted in Fig. 12 (a) and 12(b).

## 4.1 | Radiation Patterns

Simulated and measured radiation patterns of the proposed antenna for the targeted frequency is given in Fig. 13. It is clear from these radiation patterns that the proposed antenna radiates in dipolar fashion in the xy-plane and thus the E plane radiation pattern is bidirectional and the H plane (xz plane) radiation pattern is omnidirectional.

The simulated and measured results of the transmission coefficients are presented in Fig. 14. It is clear from the profiles that the antennas C to E achieve an isolation of up to 47dB in the operating frequency band. Besides, it is clear that the measured $S_{21}$ values of antenna E does curve similar to the simulated values. From the curves, it is obvious that MTM loaded antenna D has self-diplexing capacity.

Isolation is an important parameter of MIMO antenna which can be measured from envelope correlation coefficient (ECC) value. It is an indicator of interaction of element antennas of MIMO. Having a small ECC value is very important to approve the usefulness of the proposed antenna. ECC is computed using the following formula[13] 1.

$$\rho_e = \frac{|S_{11}^* S_{12} + S_{21}^* S_{22}|^2}{(1-|S_{11}|^2-|S_{21}|^2)\,(1-|S_{22}|^2-|S_{12}|^2)} \qquad (1)$$

From Fig. 15, the fabricated prototype maintains an ECC of 0.015 over the resonant frequency of 8.5GHz. The ECC value over the targeted frequency band is less than 0.025. Performance comparison with previous works are given in Table 2.

Table 2
Comparison of performance with previous works

| Ref. | No. of elements | Radiating element | Isolating structure | Edge to edge spacing (mm) | Isolation (dB) | Gain (dB) | Efficiency (%) | ECC |
|---|---|---|---|---|---|---|---|---|
| Hafezifard[2] | 2 | Meander Line | Metamaterial | 5 | 19 | 5.7 | 77.6 | Not specified |
| Marina[3] | 2 | Patch | EBG | 15 | 20 | Not specified | 85.9 | Not specified |
| Dadgarpour[4] | 2 | DRA | Metamaterial | 2.5 | 46.5 | 7.90 | 91 | Not specified |
| Qian[9] | 2 | Patch | EBG | 1 | 20 | Not specified | 83 | Not specified |
| Jian[18] | 2 | Patch | Not given | 5 | 15 | 4.2 | 60 | .02 |
| This work | 2 | Metamaterial | Metamaterial | 4 | 47 | 8.15 | 84.14 | 0.015 |

## 5 | Conclusion

An all MTM MIMO antenna has been designed and implemented to improve isolation between two NBCSRR elements. An MTM array placed in between the two MTM radiating elements plays a major roll to suppress the mutual coupling. Measured values show that an isolation of nearly 47dB is achieved with the decoupling technique in the operating frequency band of 7.525GHz to 9.1GHz. This antenna is most suitable for military applications.

# Declarations

**Funding: Not Applicable**

**Availability of data and materials:** Not applicable.

**Compliance with Ethical Standards**

**Conflict of interest** The authors declare that they have no competing interests.

**Code availability: Not Applicable**

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## Figures

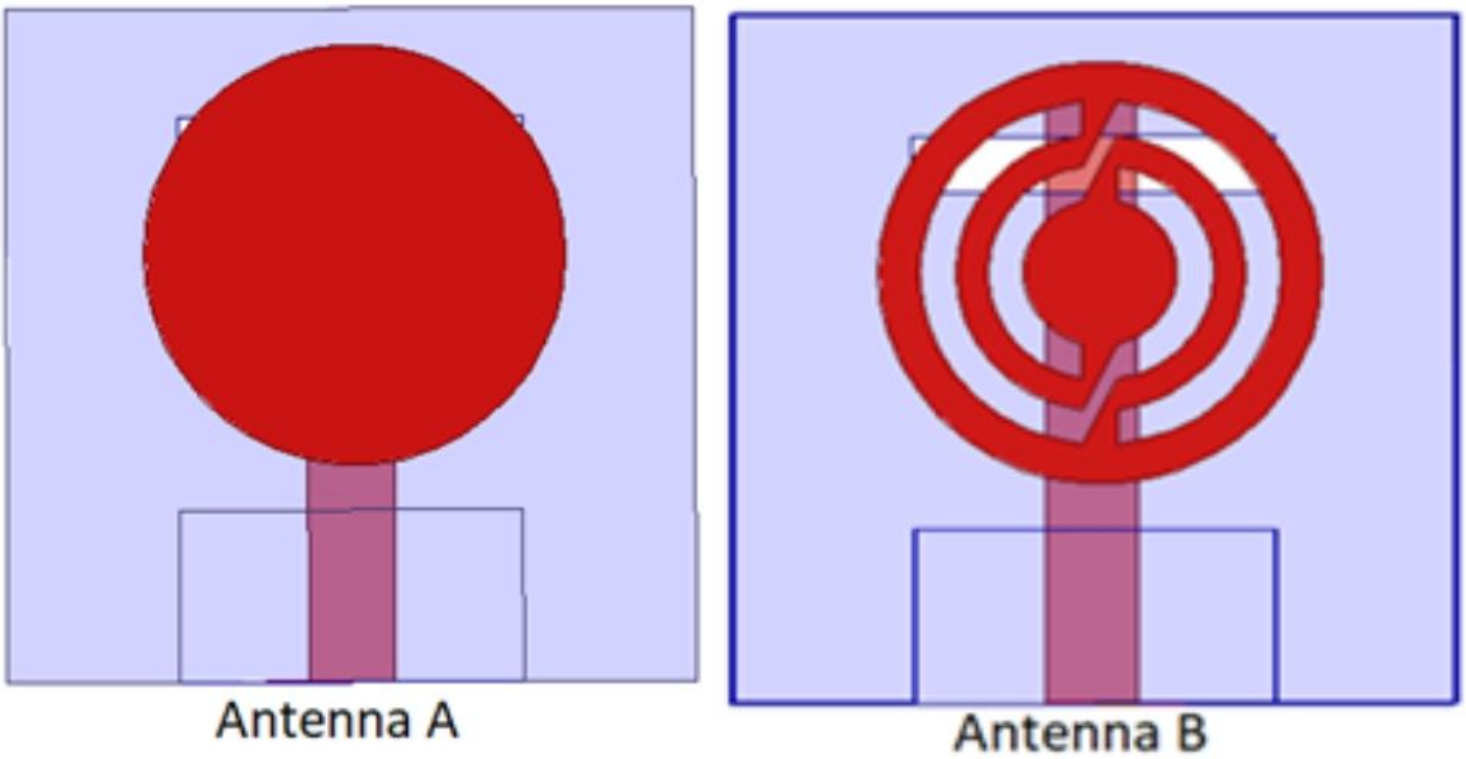



**Figure 1**

Circular patch antenna A and MTM loaded antenna B

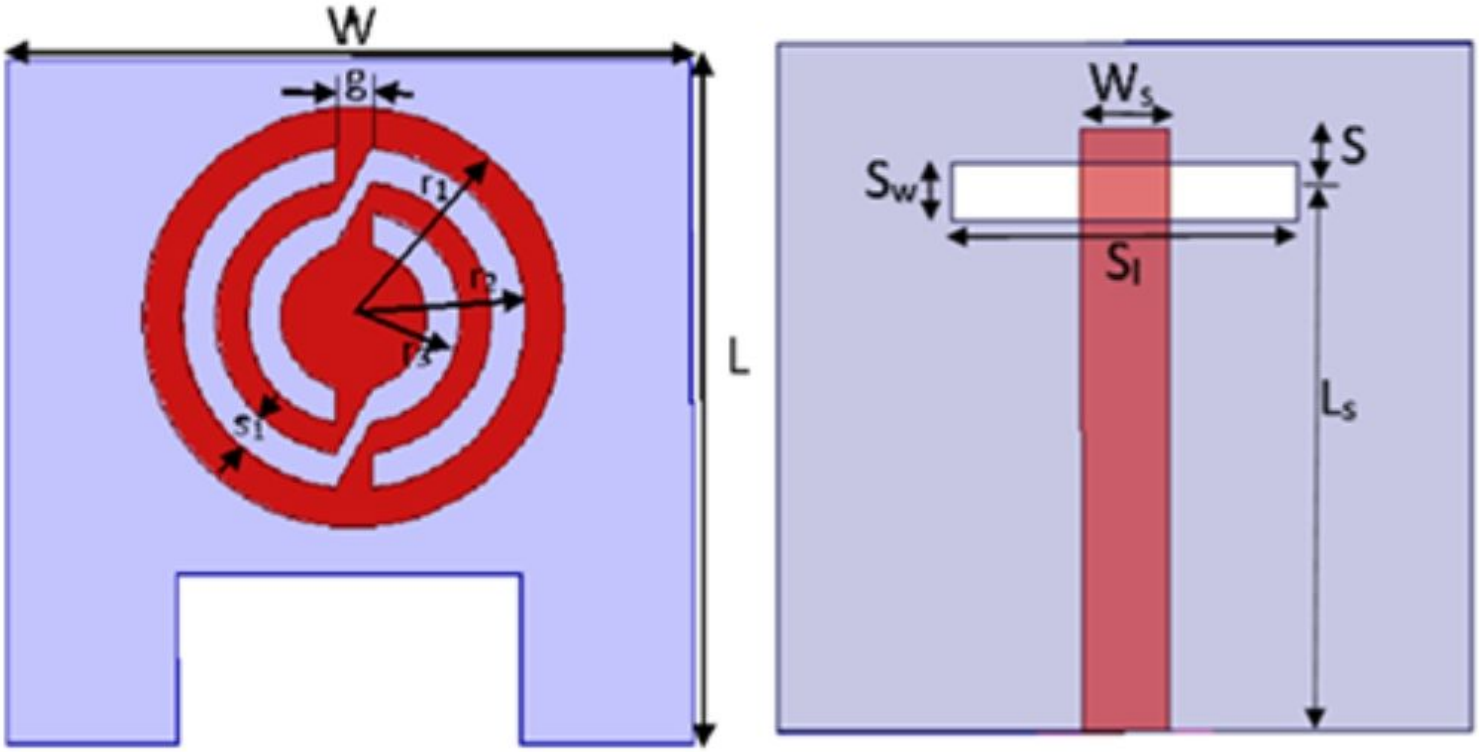



**Figure 2**

Geometry of the antenna top view, bottom with slotted ground

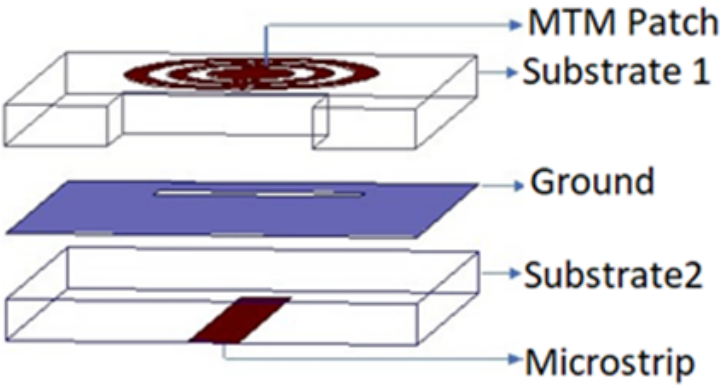



**Figure 3**

Aperture coupling with two substrates with single MTM element

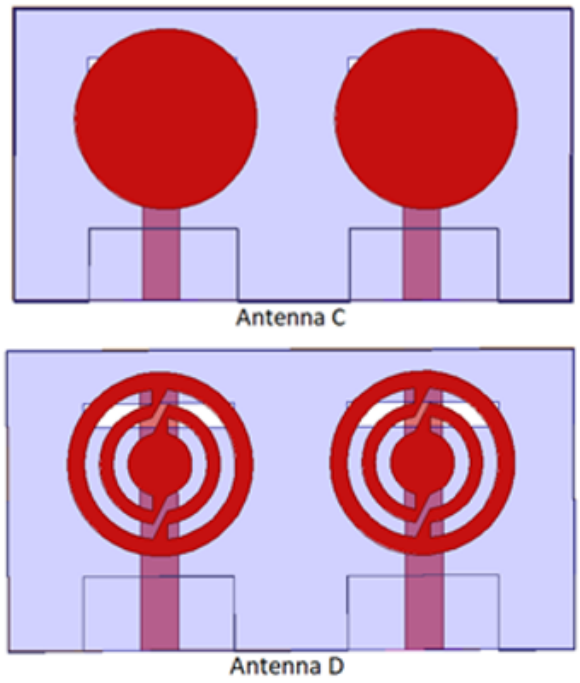



**Figure 4**

Two patch Antenna C and 2MTM element antenna D

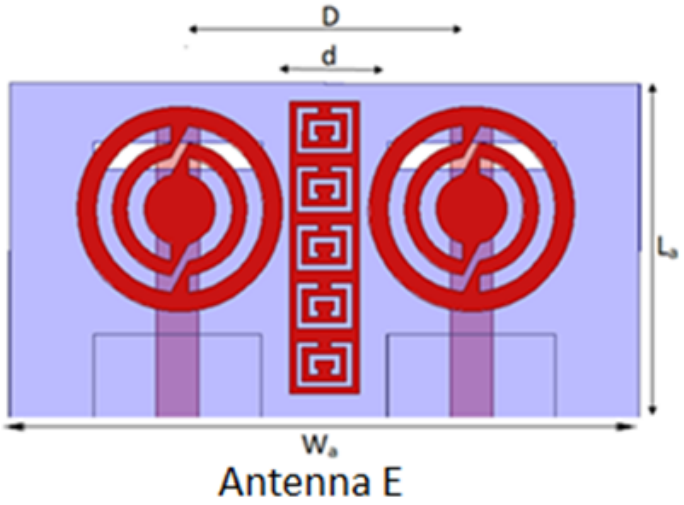



**Figure 5**

proposed antenna with two MTM element with centre CSRR array

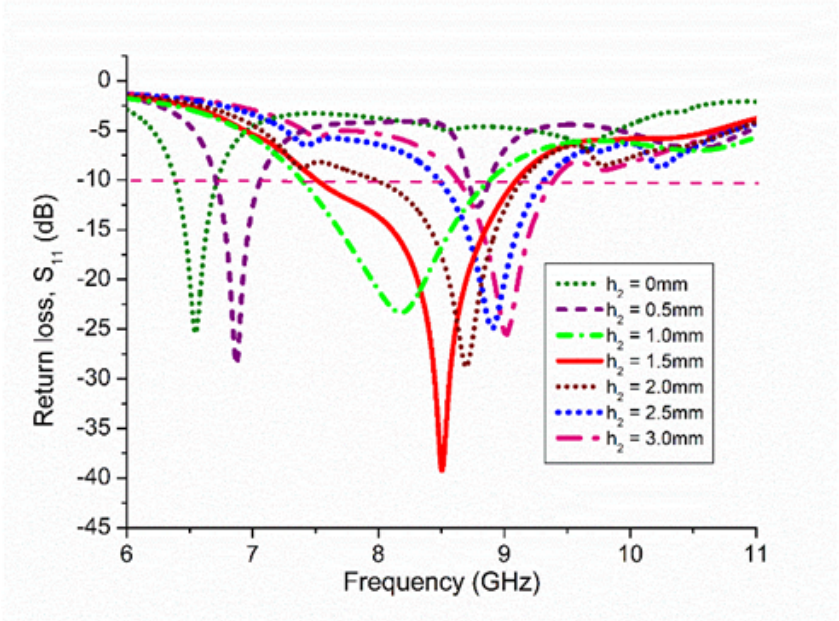



**Figure 6**

Simulated return loss variation with frequency for various values of h (air gap height)

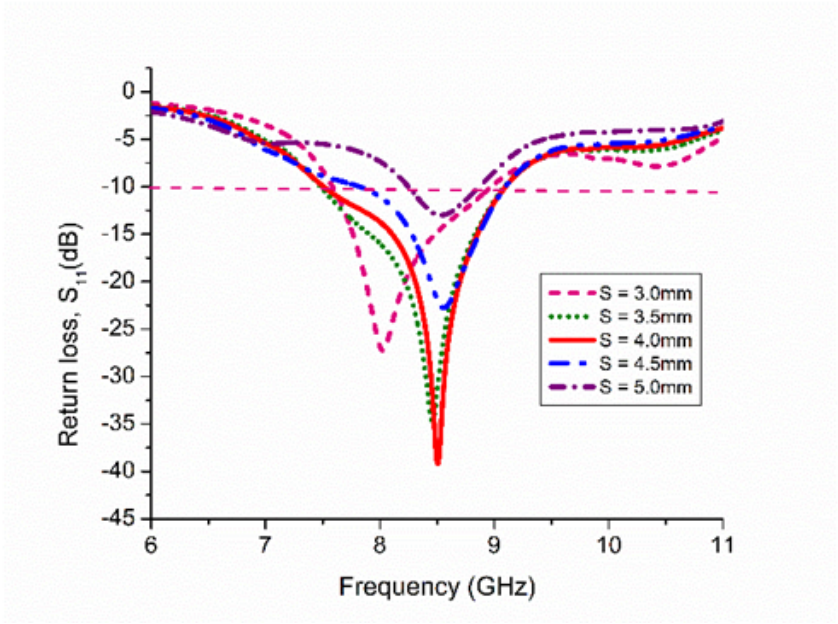



**Figure 7**

Simulated return loss variation with frequency for various values of S

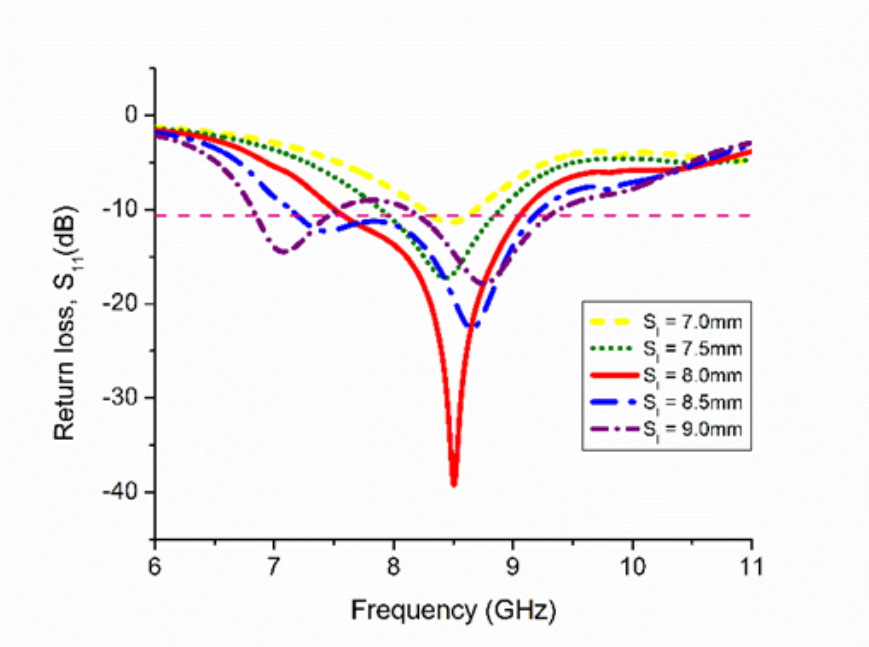



**Figure 8**

Simulated return loss variation with frequency for various values of SI

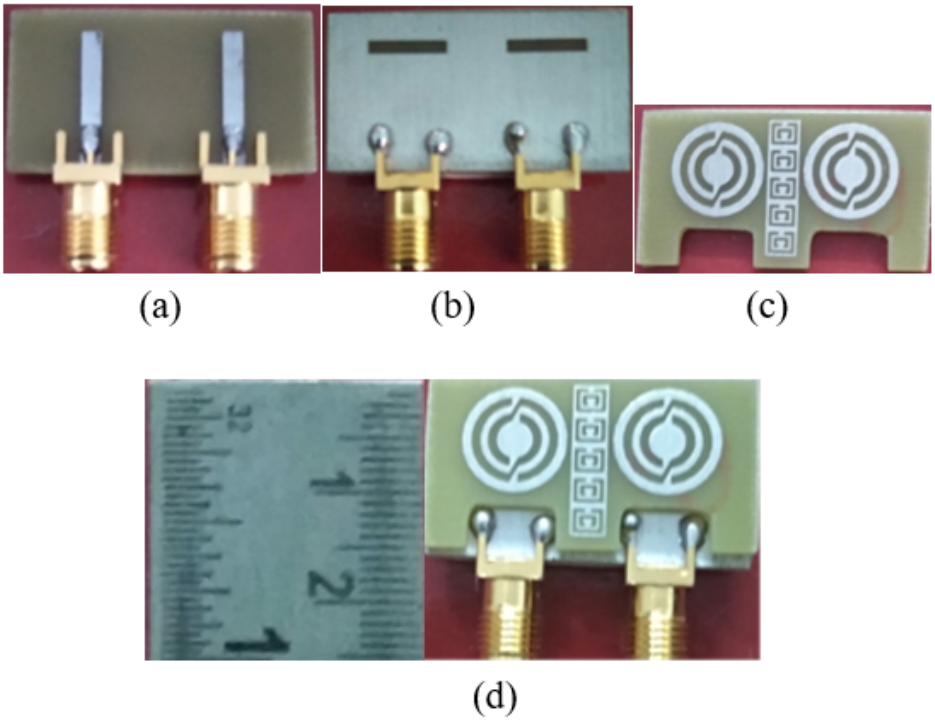



**Figure 9**

(a) Bottom of the substrate, (b) Top of the substrate, (c)Top of the superstrate and (d)Top view of the fabricated prototype

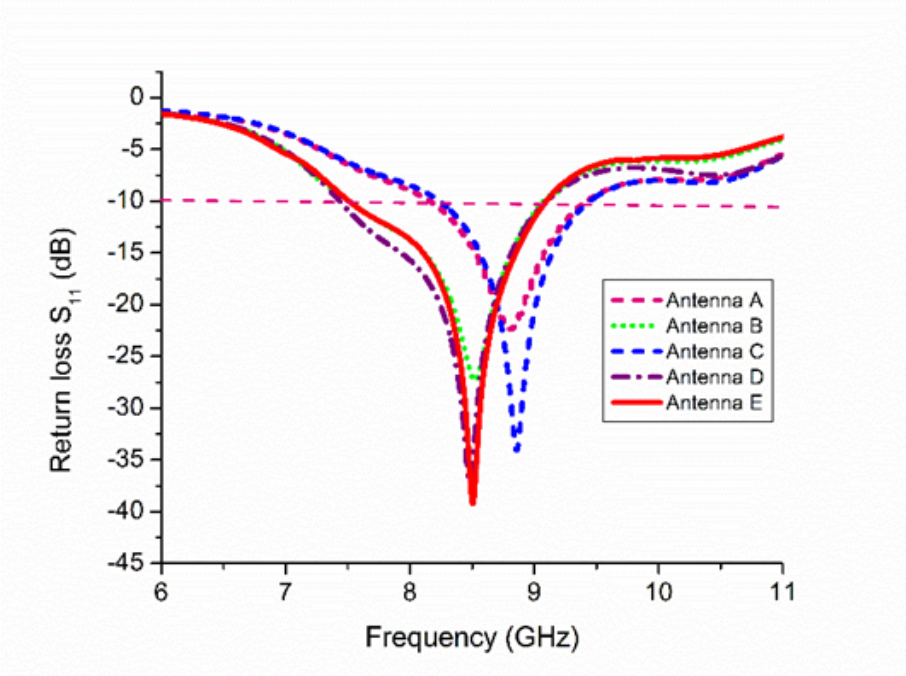



**Figure 10**

Simulated return loss variation with frequency for the antennas A to E

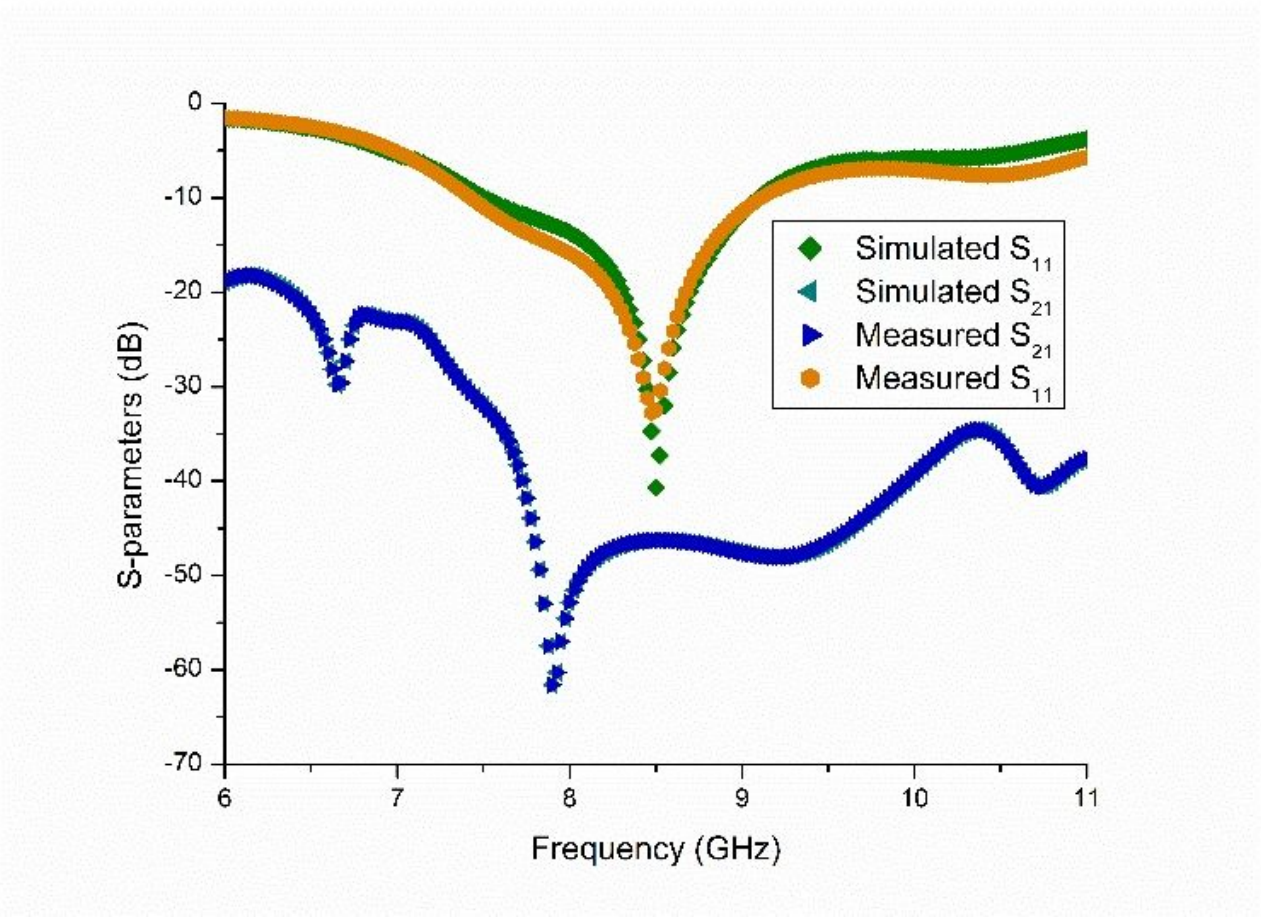



**Figure 11**

Simulated and measured S-parameters of the antenna

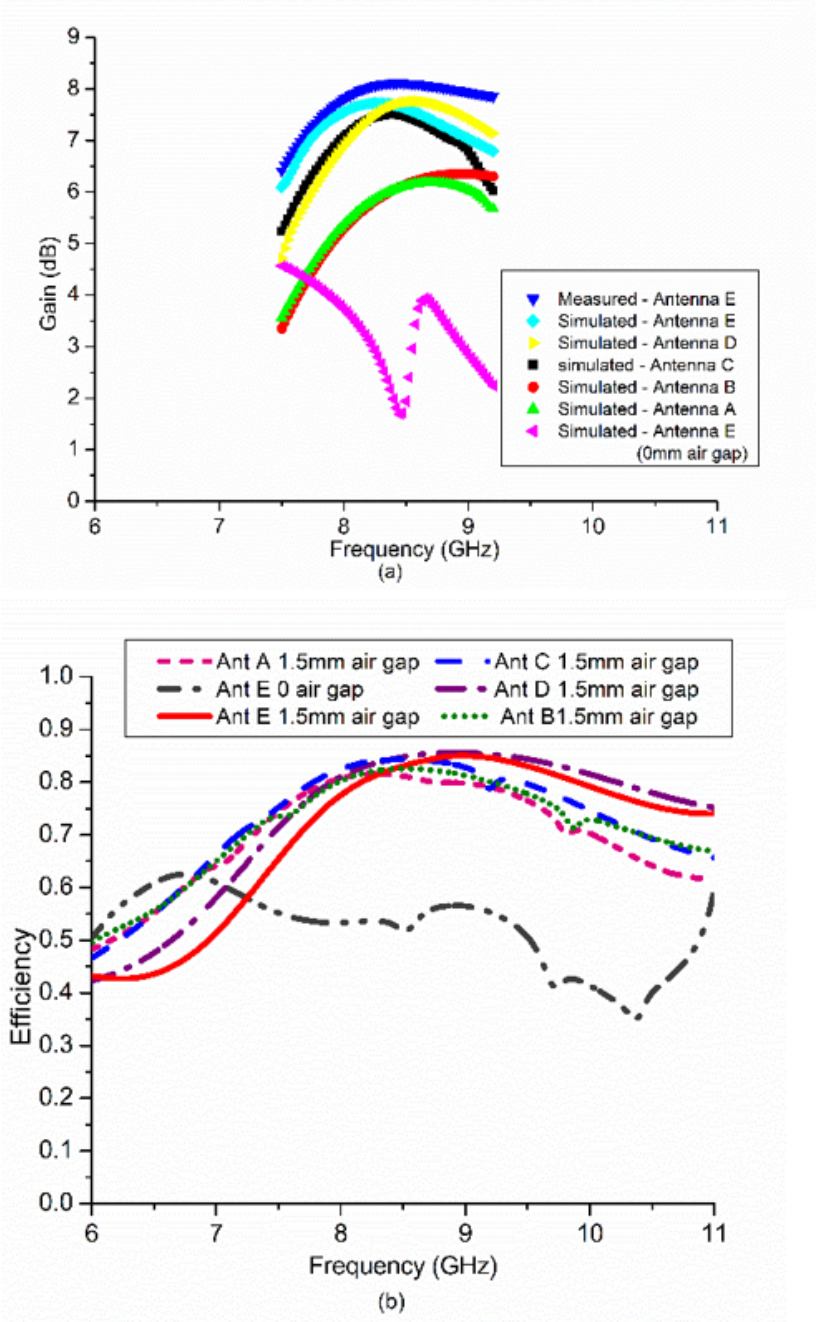
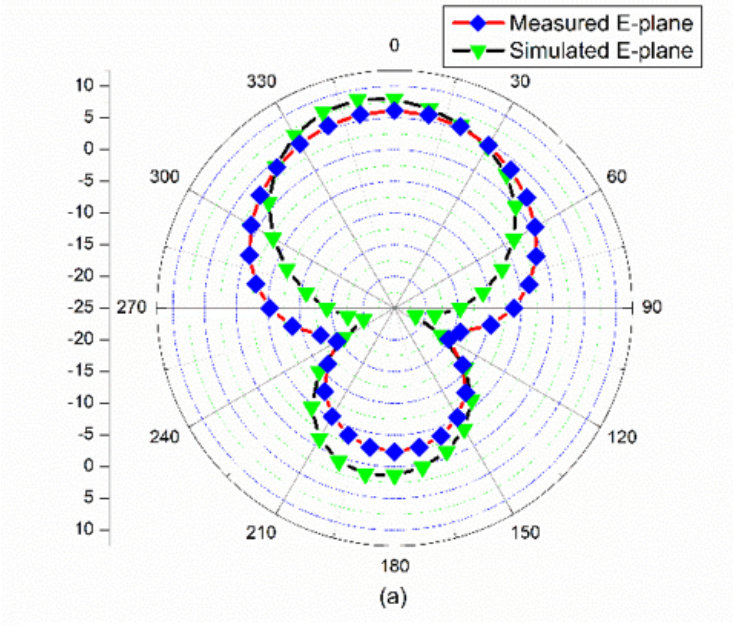
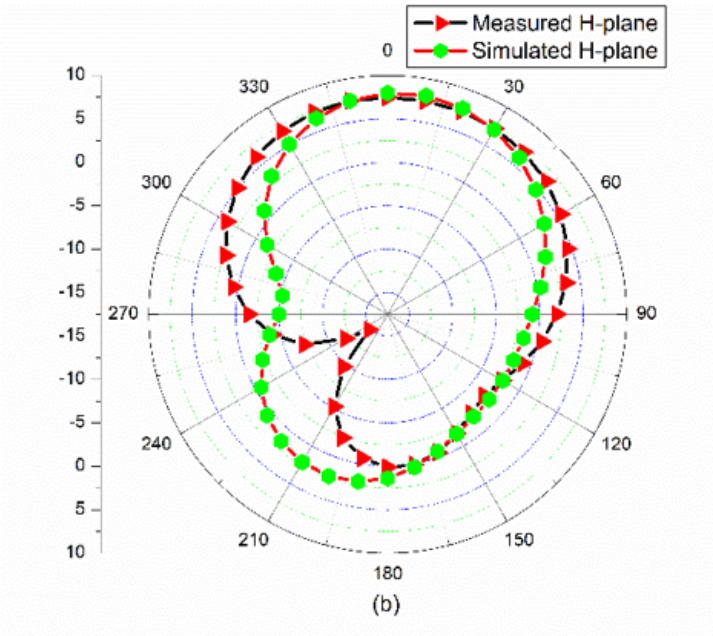



**Figure 12**

(a) simulated and measured value of the antenna Gain and (b) Efficiency of the antenna A to E in the air gap of 1.5mm and 0 mm




## Figure 13

Simulated and measured radiation patterns of the antenna (a) E-Plane and (b) H- Plane

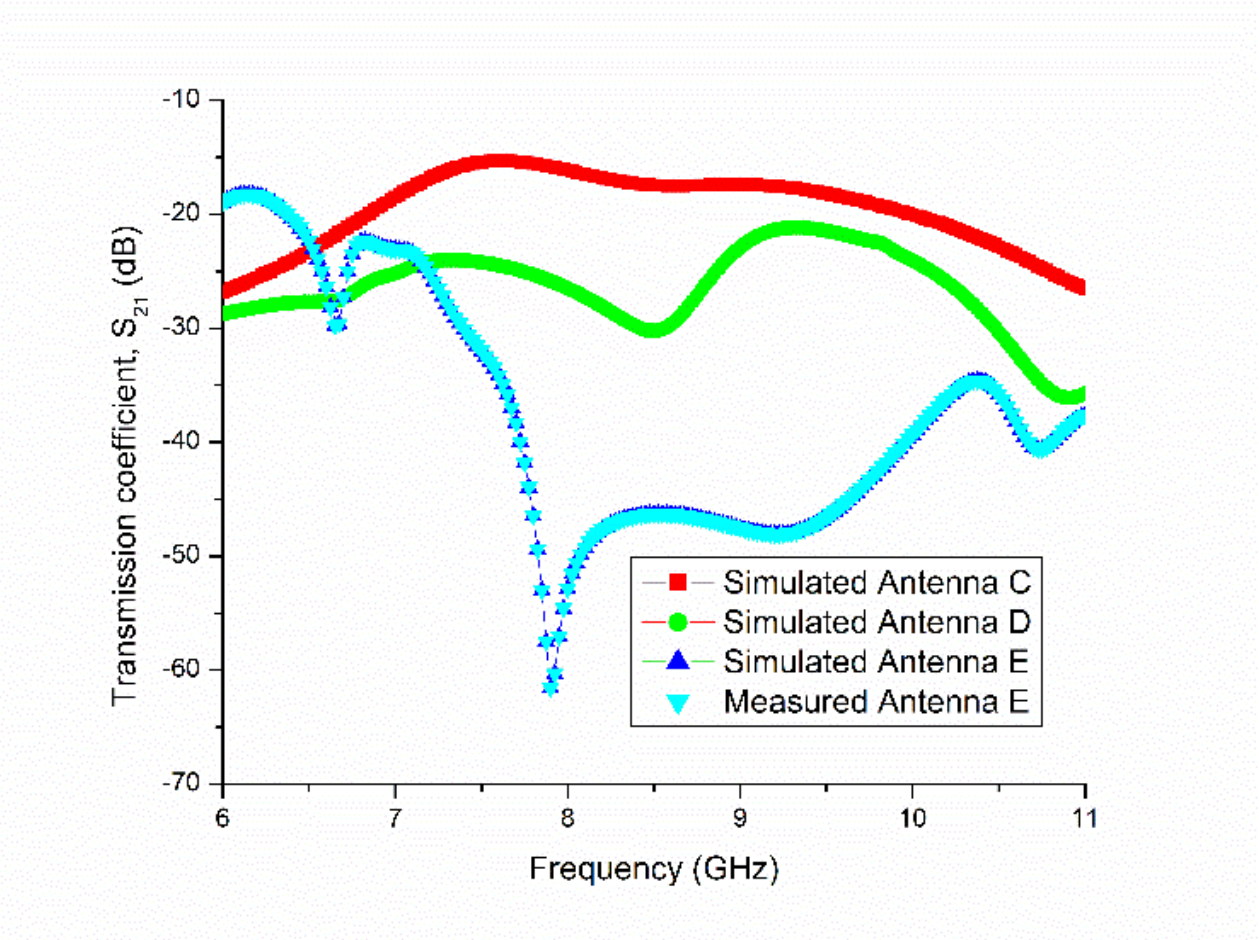



**Figure 14**

Comparison of Transmission coefficients for antennas C to E with the measured values

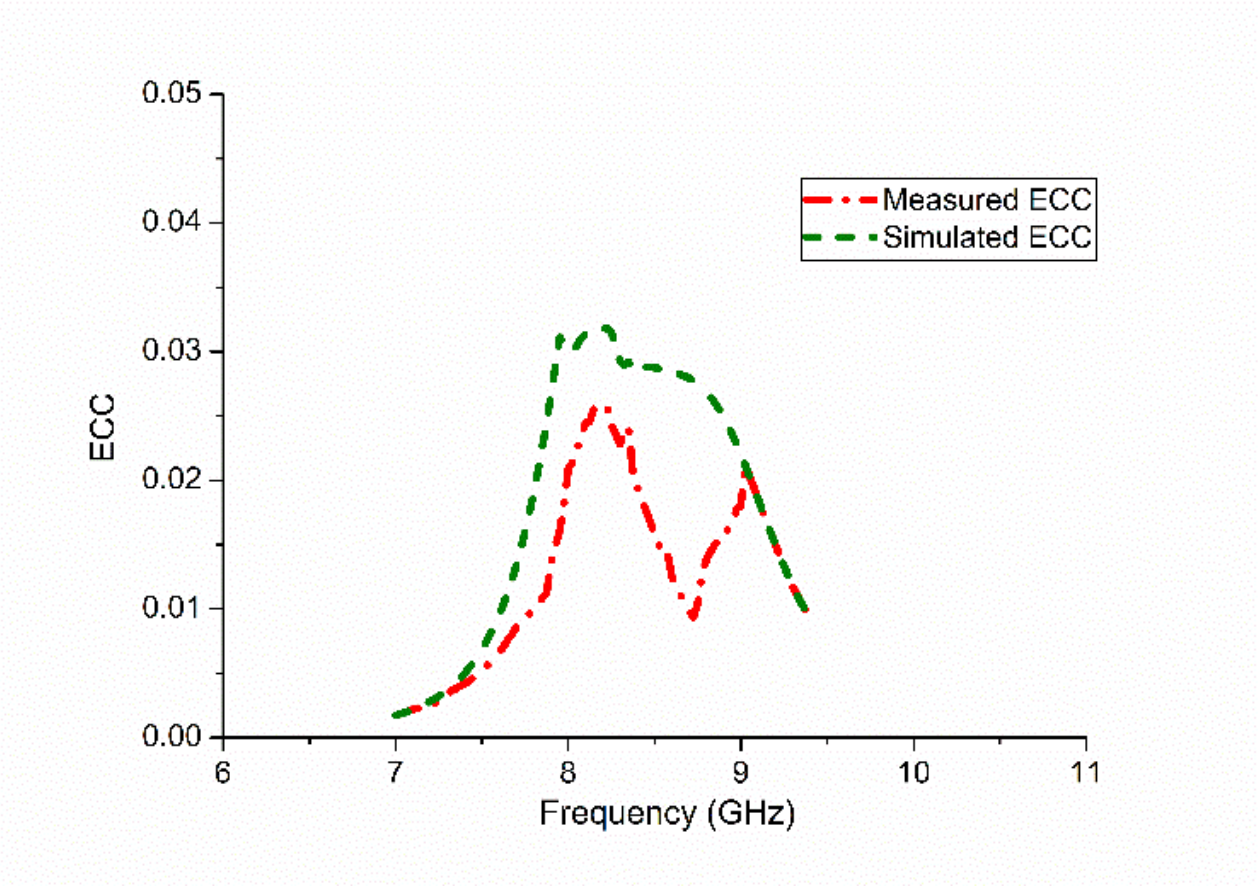



**Figure 15**

Simulated and Measured value of ECC