# CHAPTER 7

# EXPERIMENTAL INVESTIGATION ON THE PERFORMANCE OF COMPACT HILBERT CURVE FRACTAL ANTENNA ON METAMATERIAL USING CSRR

**Summary-** This Chapter focuses on the design and simulation of HCFA, CSRR, CSRR loaded HCFA, experimental results of CSRR loaded HCFA and comparison of the same with the simulation results. Though there have been many MTM based small antennas proposed so far, the use of MTM structures in fractal shaped antennas have been less attempted. Hence a compact and novel MTM loaded Hilbert Curve Fractal Antenna (HCFA) is proposed. The conventional HCFA has been designed using copper on a substrate of 20mm x 20mm x 1.6mm and simulated. A complementary slip ring resonator (CSRR) for μ negative (MNG) along with a rectangular slot for ε negative (ENG) has been designed using copper, to exhibit MTM properties (negative μ and negative ε). Later this structure has been used as a defected ground plane for the HCFA. The complete design and simulation have been performed using HFSS 3D EM simulator software and the MTM properties have been verified by a separate MATLAB coding developed for Nicolson-Ross-Weir technique. The experimental verification of the proposed fabricated antenna has been performed with network analyzer and anechoic chamber. The MTM HCFA appearing as a simple and compact structure with double side printed substrate and resonating at multiple frequencies are the novelties in this paper. In the CSRR loaded HCFA, the μ negative property is

found predominating and the structure exhibits appreciable improvement in gain, directivity, shaped radiation and down shifted resonant frequencies.

## 7.1 INTRODUCTION

Challenges remain for antennas in the development of practical implementable solutions and new antenna materials including MTMs. There have been several investigators contributing to the successful coverage of these challenges using various methods. However multiple resonances or broad band of resonance with large gain in a single MSA is not directly attainable without the use of arrays of structures (Joshi et al 2010). However, there is a limitation for such requirements because of the large physical size of the array. Therefore the investigations on the size reduction are continuously progressing and the existence of negative medium properties in several new MTM structures and the applications of same are still being explored. The concepts of SRR, MSSR and CSRR are well discussed by Joshi et al (2010), Shyam Pattnaik et al (2010), Raoul Ouedraogo and Edward Rothwell (2010) and it has been reported that the use of a LHM in near environment of MSA enhances the performances. For the verification of MTM property any of the methods found in literature (Rohde and Schwarz 2006) can be used. In this Chapter an effort has been made to demonstrate the use of a small HCFA on a CSRR structure. The CSRRs are believed to exhibit negative $\mu$ whereas thin conductor to exhibit negative $\varepsilon$ in some frequency regions. The possibility of multi-resonant property with single antenna is focused in this new approach.

## 7.2 ANTENNA DESIGN, METHODS AND MATERIALS

The investigation on the performance of MTM loaded HCFA involves a few steps. The Hilbert curves structure (Jung-Tang Huang et al 2010, Niruth Prombutr and Prayoot Akkaraaektharin 2008) has been generated as desired from the fundamental monopole antenna and then the required HCFA shape has been obtained. Then negative medium property verification of the CSRR structure has been performed. Lastly the antenna and MTM structures have been brought together for investigation. The design guidelines, antenna geometry, materials and methods outlined in Chapter 6 under the Section 6.2 are wholly applicable here too. Hence hereinafter the HCFA 1 is called the HCFA in this Chapter. The structure of MSRR, CSRR and the HCFA are shown in Figure 7.1.

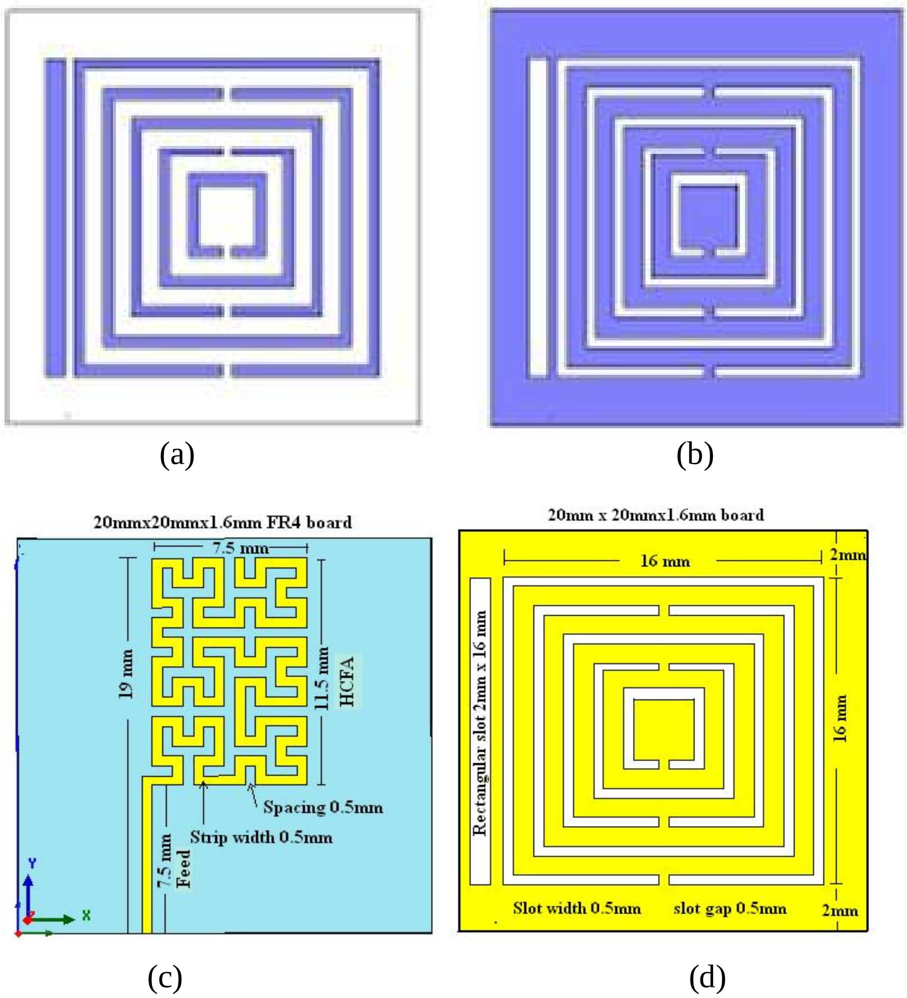



**Figure 7.1 Antenna and MTM Structures (a) MSRR (Blue Colored Lines- Conducting Rings and White Spacing-Substrate) (b) CSRR (White Spacing-Slots - Substrate and Blue Colored Portion-Conducting Part) (c) HCFA (d) CSRR as Defected Ground Plane**

The HCFA is designed using copper material on a FR4 substrate of size 20mm x 20mm x 1.6mm with $\varepsilon_r$ of 4.4. This is fed by a thin microstrip feed line. The MSRR and CSRR are duals (Shayam Pattnaik et al 2010) and hence the conducting portion in MSRR will appear as a slot in CSRR and vice versa. This CSRR is considered as a defected ground plane for the HCFA. Both the dimensions of HCFA as well as the defected ground plane made out of CSRR are the major differences in this work, when compared to the Hilbert curve used by Azad and Ali (2006).

## 7.3 SIMULATION

For the design and simulation of the proposed HCFA, the CSRR structure (for obtaining required S-parameters) and the CSRR loaded HCFA, the HFSS 3D electromagnetic simulation software has been used. The simulation in all the three cases has been swept over a frequency range from 1- 20 GHz. The HCFA has been simulated with the usual procedure as followed for any other conventional antenna. The CSRR is simulated separately on another FR4 board for verifying the MTM property. For the CSRR simulation, the set up with PEC, PMC and waveports as described in the Section 3.4.7 of Chapter 3 is used.

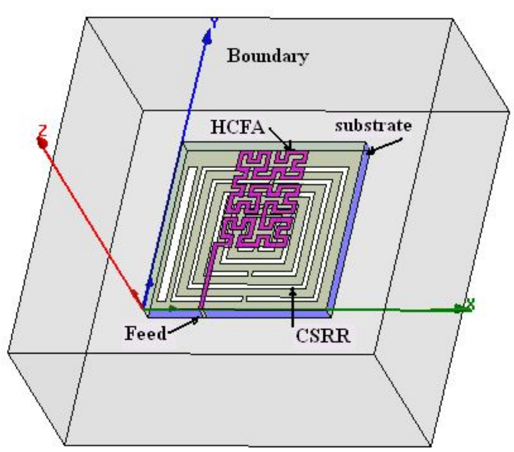


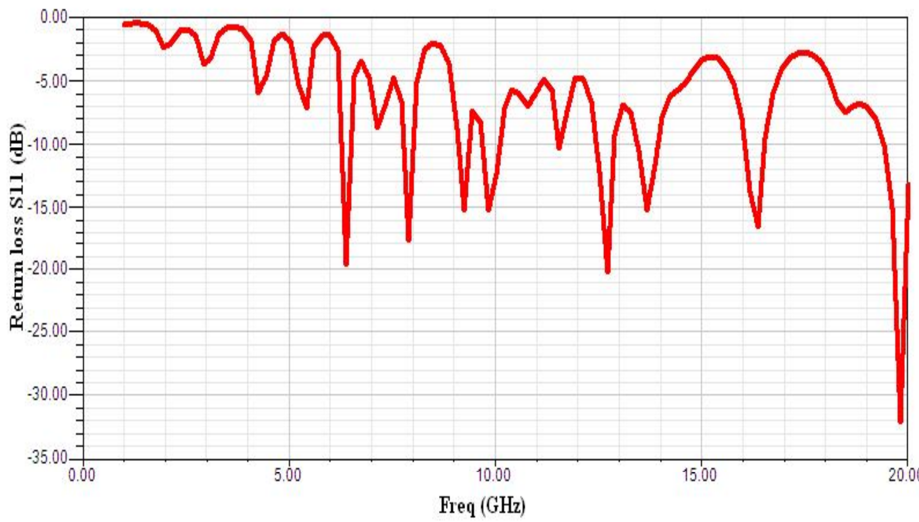

**Figure 7.2 CSRR Loaded HCFA in Simulation**

The NRW parameter retrieval approach has been used for determining the MTM property. The corresponding formulae involved for such verification have been referred from the Chapter 3 under the Section 3.4.8. The $S_{11}$ and $S_{21}$ parameters obtained from simulation have exported to MATLAB and the negative medium properties have been verified using a separate MATLAB coding. Finally the HCFA is placed on the top of the substrate whereas at the bottom side, the conventional ground plane is replaced by the already simulated CSRR pattern without making any change in either the CSRR pattern or the substrate dimensions. The CSRR loaded HCFA in the simulation set up is depicted in Figure 7.2.

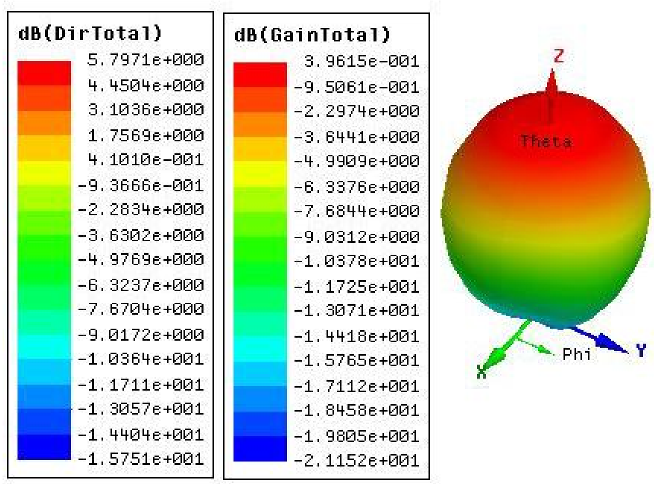
## 7.4 SIMULATION RESULTS AND DISCUSSIONS

The HCFA resonated at multiple frequencies being fractal in shape. The return loss of the HCFA resonating at multiple frequencies and the 3D polar radiation pattern are shown in Figure 7.3**.**

This antenna resonates at various frequencies from the lower region but some of the resonances are holding higher return loss values. Hence the prominent resonances at nine frequencies 6.3 GHz, 7.9 GHz, 9.3 GHz, 9.8 GHz, 11.6 GHz, 12.7 GHz, 13.9 GHz, 16.4 GHz, and 19.8 GHz with good return loss values varying between -10 dB (minimum) and -32 dB (maximum) are appreciably noted from the Figure 7.3(a). This antenna provides good matching which can be understood from the lower return loss values. As seen from the Figure 7.3(b) the gain of 0.396 dB and the directivity of 5.79 dB are only achievable with this antenna. The radiation pattern is not uniform in the $\varphi$ direction.



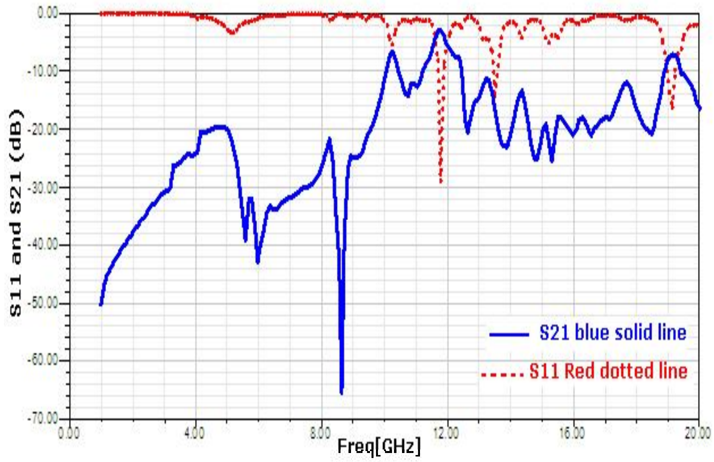

(a)



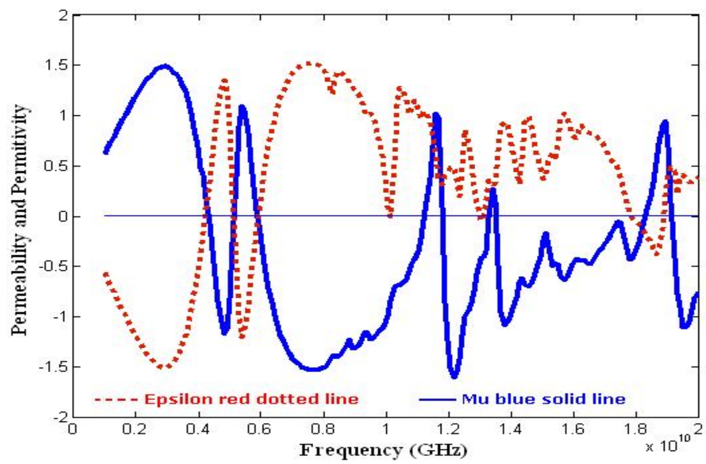

(b)

**Figure 7.3 Performance of HCFA (a) Return Loss Directivity, Gain and 3D Pattern**

The reflection ($S_{11}$) and transmission ($S_{21}$) coefficients of the proposed CSRR structure over the swept the frequency range are depicted in Figure 7.4(a). This CSRR resonates well at 11.8 GHz, 13.5 GHz and 19.3 GHz with return loss of -29 dB, -15 dB and -17 dB respectively. The relative μ and ε characteristics obtained from the S parameters are depicted in Figure 7.4(b). The structure exhibits MNG property over large.



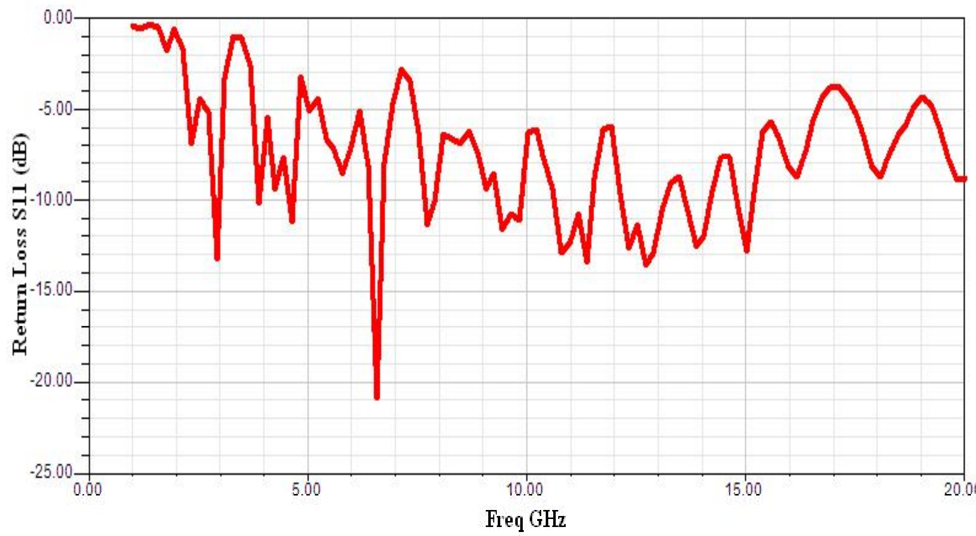

(a)



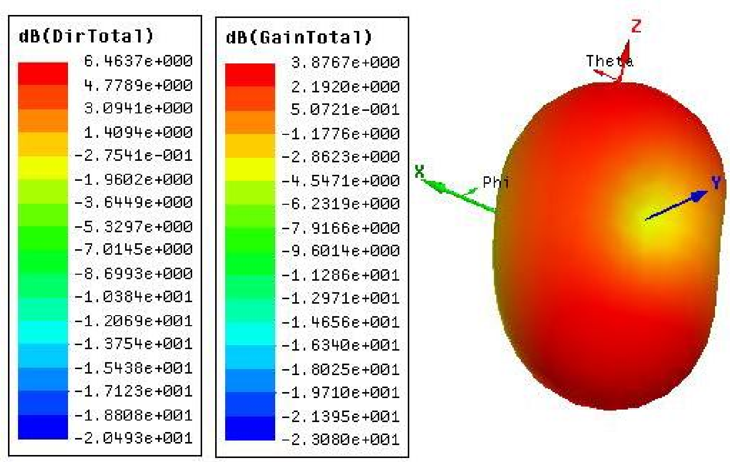

(b)

**Figure 7.4 CSRR Performance (a) Reflection($S_{11}$) and Transmission ($S_{21}$) of CSRR (Red Dotted Line $S_{11}$ and Blue Solid Line $S_{21}$) (b) Retrieved Negative Medium Properties (Red Dotted Line ε and Blue Solid Line μ)**

Frequency ranges whereas the ENG property at some few frequency regions. It is because of the shape of CSRR, the μ negative property is predominating. The frequencies at which the MTM structure exhibits negative μ and/or negative ε can be identified from the characteristics. The structure exhibits non-negative property at 4.2 GHz, 5.1 GHz, 6 GHz, 11.6 -11.8 GHz, 13.5 GHz and 19-19.3 GHz. It is interesting to note that the MTM (CSRR) loaded HCFA also resonates at multiple frequencies 2.9 GHz, 3.9 GHz, 4.7 GHz, 6.6 GHz, 7.7 GHz, 9.4 GHz, 10.8 GHz, 11.4 GHz, 12.3 GHz, 12.7 GHz, 13.9 GHz and 15 GHz with return loss values varying between -10 dB (minimum) and -21 dB (maximum) as depicted in Figure 7.5(a).




(a)



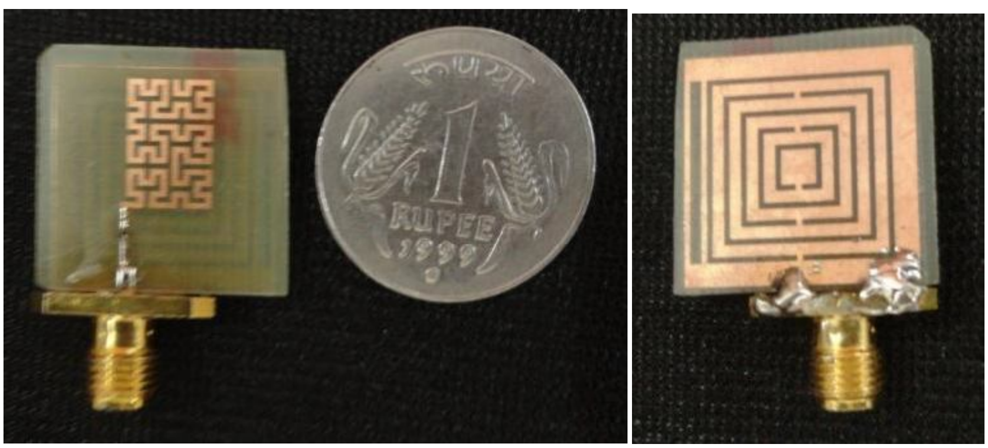

(b)

**Figure 7.5 CSRR Loaded HCFA Performance (a) Return Loss (b) Directivity, Gain and 3D Polar Pattern**

The return values corresponding to the lower frequency region were improved due to the presence of MTM structure. Since a minimum of -10 dB return loss itself provides matching, external tuning for this antenna is not required. The improved performances in terms of more resonant frequencies within the negative medium, improved gain (3.88 dB) and directivity (6.46 dB) and shaped radiation are satisfactorily achieved which can be seen in Figure 7.5(b).

## 7.5 FABRICATION

The designed CSRR loaded HCFA was fabricated using the known and simple photolithographic technique using FR4 substrate and soldered with SMA connector. The front and rear views of the fabricated structure is shown in Figure 7.6(a) - (b).



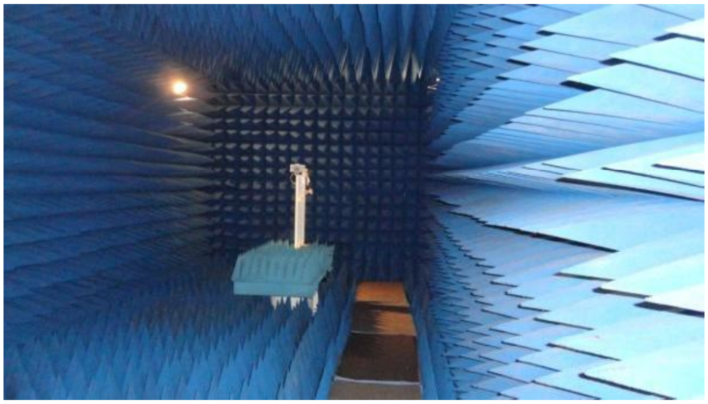

(a) (b)

**Figure 7.6 Photographs of Fabricated Antenna (a) Front View of CSRR Loaded HCFA (b) Rear View of Antenna with CSRR**

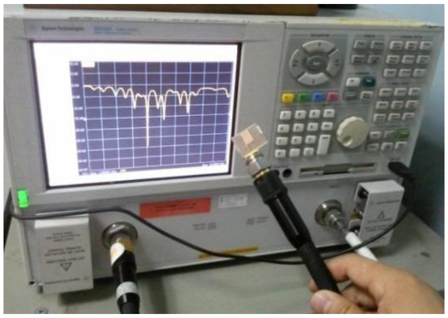
## 7.6 EXPERIMENTAL VERIFICATION

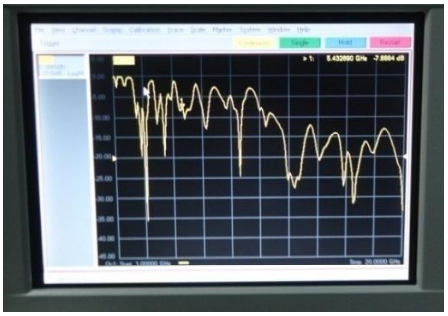
The experimental verification of the fabricated CSRR loaded HCFA have been performed in the microwave laboratory of Nanyang

Technological University, Singapore. A Vector Network Analyzer model N5230A from Agilent Technologies has been used for observing the return loss, VSWR and resonant frequencies. The radiation characteristics of the antenna have been obtained using anechoic chamber test from the same laboratory. The snapshot of the antenna under tested condition is shown in Figure 7.7(a) - (c).



(a)





(b) (c)

**Figure 7.7 Photographs of Measurement Set up (a) Antenna Kept in Anechoic Chamber (b) Screen Shot of Antenna with Network Analyzer (c) View of Measured Return Loss**

## 7.7 EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental data obtained from the measurement made using Network analyzer and Anechoic Chamber have been analyzed to understand the performance of the HCFA in the proximity of MTM. The return loss performance of HCFA in the simulation and in the measurement are agreeing as visualized from Figure 7.3(a) and Figure 7.7(c). The measurement data obtained for return loss and radiation of CSRR loaded HCFA have been analyzed elaborately in the following Sections.

### 7.7.1 Return Loss

The measured return loss characteristics of the fabricated CSRR loaded HCFA are compared with the simulation results as shown in Figure 7.8. The HCFA resonates at multiple frequencies such as 2.71 GHz (-19.43 dB), 2.995 GHz (-35.48 dB), 3.76 GHz (-11.47 dB), 4.23 GHz (-19.43 dB), 5.56 GHz (-10.29 dB), 6.98 GHz (-12.71 dB), 9.17 GHz (-24.51 dB), 10.88 GHz (-12.25 dB), 12.78 GHz (-27.52 dB), 14.39 GHz (-20.79 dB), 16.67 GHz (-31.56 dB) and 20 GHz (-33.53 dB) with appreciable return loss values as indicated in parentheses.

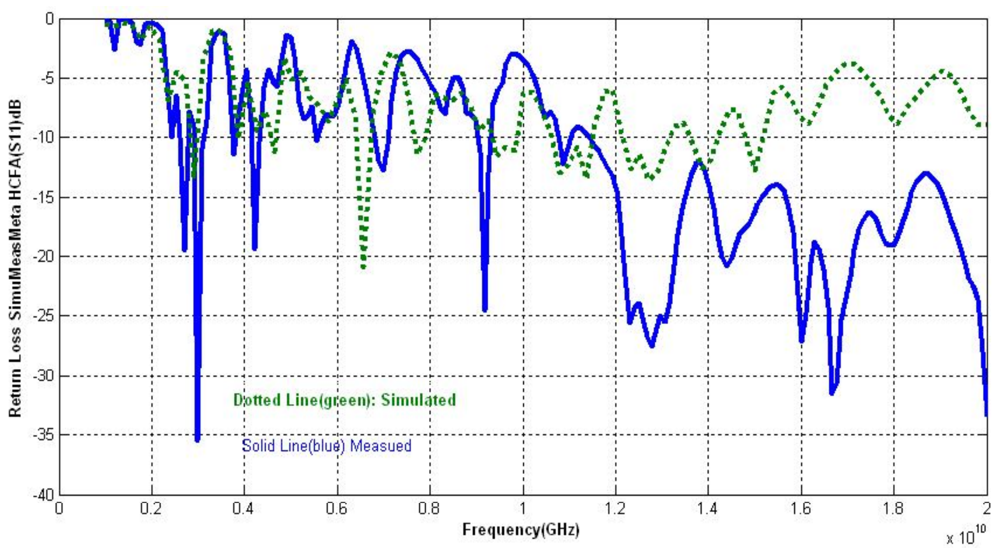
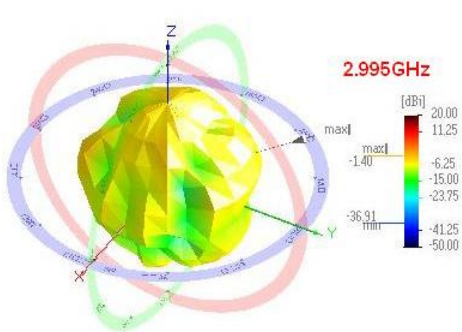



**Figure 7.8 A Comparison of Simulated and Measured Return Loss Characteristics of CSRR Loaded HCFA**

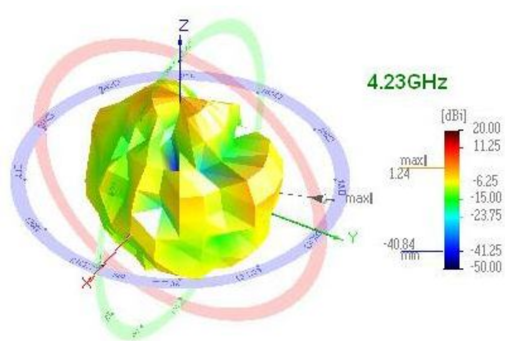
**Table 7.1 Measured Characteristics of CSRR Loaded HCFA**

| $f_r$ (GHz) | RL (dB) | $f_u$ (GHz) | $f_l$ (GHz) | BW (GHz) | BW % | VSWR |
|---|---|---|---|---|---|---|
| 2.995 | -35.48 | 3.7 | 2.97 | 0.73 | 24.37 | 1.12 |
| 4.23 | -19.43 | 4.3 | 4.15 | 0.15 | 3.55 | 1.27 |
| 6.98 | -12.71 | 7 | 6.8 | 0.2 | 2.86 | 1.43 |
| 9.17 | -24.51 | 9.2 | 9.05 | 0.15 | 1.63 | 1.51 |
| 12.78 | -27.52 | High | 11.4 | Large | Good | 1.32 |
| 14.39 | -20.79 | High | 11.4 | Large | Good | 1.13 |
| 16.67 | -31.56 | High | 11.4 | Large | Good | 1.22 |

It also provides broad bandwidth after 11.4 GHz which is really an interesting feature in this antenna. The return loss ($S_{11}$ in dB) at the majority of the resonances remains much reduced (-35.48 dB being the lowest) when compared to the simulated results. This can be well noticed in the Figure 7.8. The experimental and simulated resonances are in good agreement. The Table 7.1 shows the measured values for some selected resonant points. The bandwidth % is much appreciable at 2.995 GHz. The VSWR of 2:1 is maintained at all resonant frequencies.

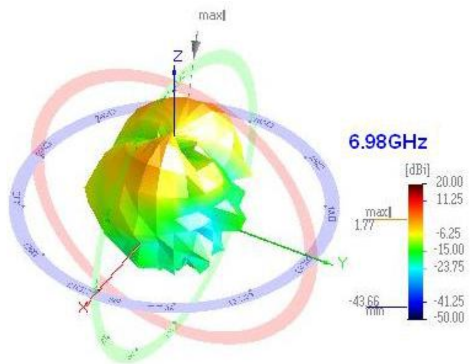



(a)

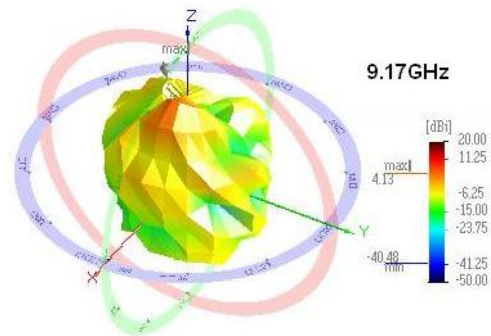



(b)

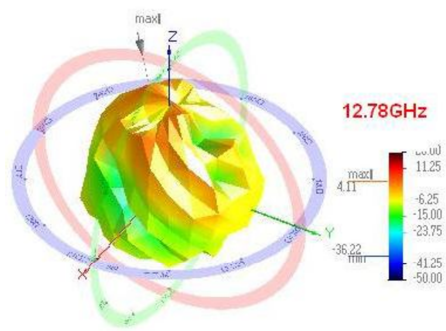
**Figure 7.9 (Continued)**



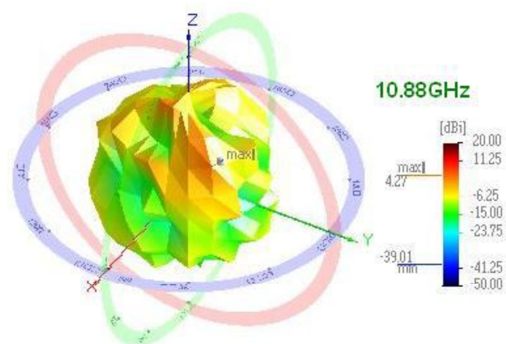

(c)



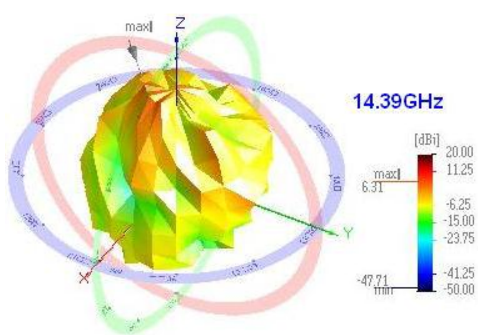

(d)



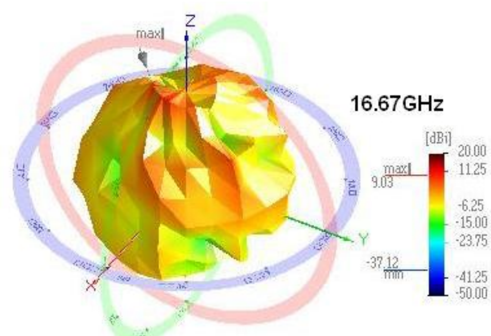

(e)




(f)

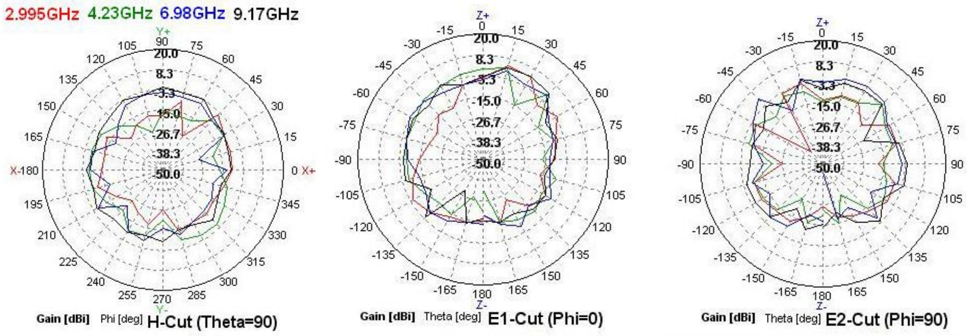



(g)

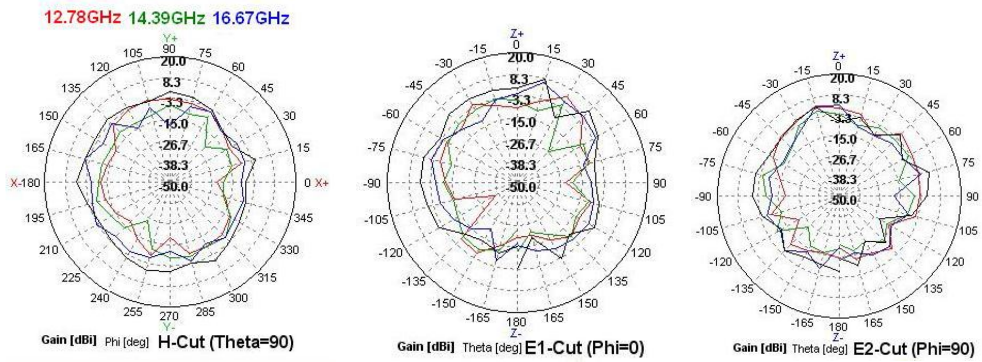



(h)

**Figure 7.9 (Continued)**




(i) (j) (k)




(l) (m) (n)

**Figure 7.9 Measured Radiation Characteristics of CSRR Loaded HCFA (a) - (h) 3D Radiation Plots at 2.99 GHz, 4.23 GHz, 6.98 GHz, 9.17 GHz, 12.78 GHz, 14.39 GHz and 16.67 GHz Respectively (i) - (k) H cut($\theta$ = 90˚), Ecut($\varphi$ = 0˚) and E cut($\varphi$ =90˚) Patterns Each at Resonant Frequencies 2.99 GHz, 4.23 GHz, 6.98 GHz and 9.17 GHz Respectively (l) - (n) H cut($\theta$ = 90˚), E cut($\varphi$ = 0˚) and E cut($\varphi$ =90˚) Patterns Each at Resonant Frequencies 12.78 GHz, 14.39 GHz and 16.67 GHz Respectively**

### 7.7.2 Radiation Pattern

The radiation characteristics of the fabricated CSRR loaded HCFA are shown in Figure 7.9 for some selected resonant frequencies. The measured radiation parameters are shown in Table 7.2. It can be noticed that the radiation spreads in all directions and the peak gain reaches a maximum of 8.8 dBi in this antenna. The pattern provides maximum radiation in the θ and Φ directions as indicated in the Table 7.2. The peak gain of 8.8 dBi is reached at θ of 30° and Φ of 285° directions in the horizontal polarization. The peak gain of 6.31dBi is achieved when θ is 15° and Φ is 300° in the vertical polarization.

**Table 7.2 Measured Radiation Properties of CSRR Loaded HCFA**

| $f_r$ (GHz) | Theta Pol(H) | | | | Phi Pol(V) | | | |
|---|---|---|---|---|---|---|---|---|
| | Peak Gain (dBi) | η % | (θ°) | (Φ°) | Peak Gain (dBi) | η % | (θ°) | (Φ°) |
| 2.995 | -1.4 | 17.8 | 60 | 105 | 3.05 | 37.23 | 60 | 330 |
| 4.23 | 1.24 | 20.85 | 75 | 90 | 2.96 | 40.87 | 75 | 135 |
| 5.56 | 1.77 | 13.81 | 30 | 185 | 2.17 | 21.63 | 45 | 285 |
| 9.17 | 4.13 | 15.62 | 15 | 0 | 3.52 | 27.62 | 75 | 105 |
| 12.78 | 4.11 | 26.27 | 15 | 255 | 4.06 | 18.5 | 15 | 300 |
| 14.39 | 6.31 | 33.96 | 15 | 300 | 8.8 | 48.08 | 30 | 285 |
| 16.67 | 0.11 | 19.57 | 75 | 300 | 2.22 | 24.91 | 15 | 90 |

A comparison of the proposed antenna with that designed by the previous investigator is made available in Table 7.3. The performance of HCFA is found to be superior in terms of multiple resonances in a single miniature antenna when compared with that of Ahmad Sulaiman et al (2010).

**Table 7.3 Performance Comparison of HCFA**

| Comparison | Proposed CSRR HCFA | Ahmad Sulaiman et al (2010) |
|---|---|---|
| Type | Metamaterial antenna<br>CSRR loaded HCFA | Metamaterial antenna<br>MSRR loaded circular patch antenna |
| MTM structure | Square ring (gap) N=5<br>g=s=0.5mm w=1mm | Square ring N=2<br>g=s=w=2mm |
| Antenna shape | Modified 3$^{rd}$ iterated Hilbert curve | Circular patch |
| Antenna size | 19mm x7.5mm | 16.5mm radius |
| Substrate | FR4, 20mm x 20mm, double side printed board,<br>h=1.6mm, $\varepsilon_r$ = 4.4 | FR4, 20mmx20mm, double side printed, h=0.25mm $\varepsilon_r$ = 4.9 |
| Feed | Microstrip fed | Microstrip fed |
| Simulation | HFSS | CST microwave studio |
| MTM verification | NRW | NRW |
| Sweep frequency | 1-20 GHz | 1- 4 GHz |
| Antenna Resonance | Multiple resonances: 9 | Single resonance |
| Resonance of MSRR | Triple | Single resonance, -3.09dB |
| Resonance of MSRR loaded antenna | Multiple resoances:12 | Single: 4.7GHz (-24.2dB)<br>(gain:1.9dBi, dir:5.66dBi) |
| Bandwidth & % BW | At 2.99 GHz, 730 MHz<br>Large BW after 11.5 GHz (measured) | 200 MHz |
| Measured Resonance of MSRR loaded antenna | Network Analyzer & Chamber<br>Multiple resonances: 12 | Measured: nil |
| Advantages | Multiple resonances, low return loss, improved gain, directivity, size reduction | Reduction in antenna size due to MTM |
| Applications | S to Ka band wireless applications implantable devices | S band wireless applications |

## 7.8 CONCLUDING REMARKS

The objective of design and simulation of HCFA and then improving its performance with the use of CSRR structure as a defected ground plane has been satisfactorily simulated and experimentally verified. The performances of the HCFA are in compliance with multiple resonant properties. With CSRR as a defected ground plane, noticeable improvements were achieved in terms of more resonant frequencies, improved peak gain and good radiation. The return loss values obtained for majority of resonant frequencies are much lower indicating well matched situations. This is because of the existence of the negative $\varepsilon$ and negative $\mu$ properties in the prepared MTM. This kind of antenna can be of use in multi-integrated wireless applications requiring single antenna for multiple resonances.