CHAPTER – 4

METAMATERIAL BASED MINIATURIZED PLANAR ANTENNA DESIGN

4.1 OBJECTIVE

4.2 A METAMATERIAL INSPIRED MIMO ANTENNA SYSTEM WITH HIGH PORT ISOLATION

4.3 A COMPACT MINIATURIZED TRI-BAND CIRCULAR PATCH ANTENNA LOADED WITH METAMATERIALS

4.4 CHAPTER SUMMARY

REFERENCES
4.1 Objective

In this chapter, the possibility of using metamaterial with potential application to radiating systems has been investigated in detail. As discussed in chapter 2 and 3, left handed material or metamaterial (MTM) is a periodic composite structure exhibiting unusual physical properties with the unit cell dimension much smaller than the free space wavelength. It allows designing numerous novel dual or multi-band resonant antennas with enhanced antenna performances and smaller dimensions. The MTM unit cell can be used as basic building element for designing multi resonant small metamaterial inspired antenna or can also be used as reactive loading on the radiating patch, or on the ground plane for designing low-profile and efficient electrically small multiband antennas.

In the first half of the chapter, a dual-band two-element metamaterial-inspired MIMO antenna system with reduced mutual coupling for LTE and WiMAX applications has been exhibited. Each antenna element consists of a square–ring slot radiator (SRSR) encircling a complementary split ring resonator (CSRR). The fabricated prototype system shows two bands covering LTE 2300 and WiMAX bands. To achieve high port isolation between the two antennas, a metamaterial decoupling structure, consisting of complementary two-turn spiral resonator (CSR2) unit cells are introduced in the ground between the two antenna elements. The passive characterization of two-antenna system was performed using the electromagnetic full-wave simulations. Finally, the simulated results are confirmed by experimental measurements. In the second section, a novel method to achieve multi-band performance for both reduced and conventional size circular microstrip patch antenna (CPA) loaded with metamaterial unit cell have been presented. The proposed tri-band CPA is based on metamaterial structure called complementary skewed omega type resonator (CSOR). The conventional CPA operating with 5.1GHz loaded with a pair of symmetric CSORs on the ground plane excite three working frequencies. Numerical simulation of the proposed antenna shows that the resonance frequencies of each band can be tuned independently. Good matching and stable radiation pattern with good gain have been achieved in both the working bands. A good agreement simulated and measurement results validate the design method.
SECTION A

4.2 A Metamaterial Inspired MIMO Antenna System with High Port Isolation

4.2.1 Introduction

To attain higher data rates, multimedia and multiband capabilities, cutting edge wireless systems will depend on the use of multiple-input–multiple-output (MIMO) antenna systems incorporated inside the different wireless terminal devices [1]. Furthermore, multiband requirements and physical dimension constraints in most wireless device call for miniaturization of multi-antenna system. Due to constraints on the physical dimensions of devices; the distances between the multiple antennas are usually small.

Consequently, the narrowly separated antennas can cause high mutual coupling, it is extremely hard to incorporate multiple antennas intently in a size confined device at the same time as maintaining good isolation amongst neighboring radiating elements that influences the compact inter-element spacing can cause strong mutual coupling between the antennas, making it hard to incorporate numerous antenna in a size limited device while keeping up good isolation between adjacent adjoining transmitting elements. High mutual coupling can adversely affects the overall diversity performance of the MIMO systems [2]. To enhance port isolation, many approaches have been investigated, in addition to the use of decoupling network [3], slotted meander-line resonator (SMLR) [4], neutralization line [5-6], coupling parasitic element [7], orientation of antenna element [8], electromagnetic bandgap (EBG) structures to decrease the surface wave [9–11], DGS [12-14] and the utilizing sub- wavelength MTM resonators [15-18].

MTM are artificially engineered periodic structures that can exhibit negative permittivity or permeability or both properties with sub-wavelength dimension. MTM can be designed to exhibit band gaps in their dispersion diagram [19]. This property can be utilized to isolate firmly stuffed antennas. Accordingly, the MTM ought to be outlined legitimately have a band notch at the preferred frequency band. While most of the works
on improving the isolation between two antennas focus on single operating band, modern wireless communication systems have evolved to support multi-band operation. Dual-band dual-element MIMO antenna system incorporating decoupling structures have been proposed [20-28].

Recently, compact resonant antennas using metamaterial (MTM) techniques have played an increasingly important role to improve their performance for electrically small designs [29], which provide a conceptual route for dual-band and multi-band operations. MTM antennas are very useful for multi antenna systems such as MIMO and diversity systems due to their compact size. These MTM inspired antennas can be constructed by using split ring resonators (SRRs) and complementary SRRs [30-37].

In this section of the chapter, a compact dual-band dual-element metamaterial-inspired MIMO antenna system with high port isolation that covers LTE 2300 band and 3.5GHz WiMAX band that is suitable for next generation handheld wireless terminals has been presented. The designed antenna is composed of an inner complementary split ring resonator (CSRR) and an outer square–ring slot radiator (SRSR) to operate in two different resonant frequency band at 2.4/3.5 GHz. To accomplish high isolation among the two radiating components, a metamaterial decoupling structure, consisting of complementary two-turn spiral resonator (CSR2) unit cells are introduced in the ground between the two antenna elements. The passive characterization of two-antenna system was performed using the electromagnetic full-wave simulations. The simulated results are affirmed by experimental measurements. Details of the design considerations and experimental results of the MIMO antenna system are presented and discussed.

4.2.2 Dual-Band MIMO Antenna System

The configuration of the dual-band dual-element MIMO antenna system is shown in figure 4.1, which is designed on a FR4 substrate ($\varepsilon_r = 4.2$, $\tan\delta =0.001$) with a thickness of 0.8 mm. The designed MIMO system is formed by two printed slot antennas separate by a distance $P$. The overall size of each printed slot antenna element is ($W_g \times L_g$) = 19 x
26 mm² and the total area of the dual-element MIMO antenna system is \((W_g \times L_g) = 43 \times 26\) mm² with a separation \((P)\) of 10 mm between the nearest edges of the two outer rings. The designed structure of dual-band antenna used in the proposed dual element MIMO antenna system shown in figure 4.2. Each dual-band antenna element consists of two loops: an outer loop and inner loop. An outer loop consists of square-ring slot radiator (SRSR) inner loop consists of complementary split ring resonator (CSRR), where the outer length of SRSR and CSRR are taken as ‘\(a\)’ and ‘\(2r\)’ respectively.

Both the SRSR and CSRR etched on the bottom side of the ground plane. A 50 Ω transmission feed line is used to excite the antenna. The optimized parameters of the metamaterial inspired antenna element are listed as follows: \(W_g=19\) mm, \(L_g=26\) mm, \(a=14.4\) mm, \(r=5.1\) mm, \(w=d=0.5\) mm, split gap \((g)\) = 0.4 mm respectively.

For better impedance matching of proposed dual band antenna, we have used tapered impedance transformer feed line. The width of the tapered transmission line and additional tapered transmission lines width can be correlated as [38].

\[
W_n = \xi^n \times W_f \quad \text{ (n=1, 2)}
\]  

(4.1)

where the optimized coefficient constant \((\xi=0.78)\) is calculated by the parametric study and fine tuning using electromagnetic (EM) solver. The width of the tapered transmission line at the feed point is \(W_f\) (equal to 2.1 mm) and total tapered transmission line feed length \((L_f)\) = 15.2 mm.

Figure 4.1: Configuration of dual-element MIMO antenna system.
The proposed antenna performance has been investigated and optimized by using CST MWS electromagnetic (EM) solver. It is presumed that the proposed antenna should possess dual-band operation with omni-directional radiation pattern by maintaining a compact size. The primary idea is that the lower resonant frequency is achieved by inner complementary split ring resonator (CSRR) while higher resonant mode can be provided through the outer square–ring slot radiator (SRSR). The approximate dominant resonant frequency of SRSR can be calculated by using [39].

\[
f_{\text{SRSR}} \approx \frac{1.5c}{2[a + (a - w)]} \times \sqrt{\frac{1 + \varepsilon_r}{2\varepsilon_r}}
\]

(4.2)

where \( \varepsilon_r \) is relative permittivity of the substrate, \( c \) is the speed of light in free space, and \( w \) is slot width of the SRSR.

The fundamental resonant frequency of CSRR can also be calculated by using the transmission-line model method is given by [40-41].

\[
f_{\text{CSRR}} \approx \frac{c}{2\pi^2} \sqrt{\frac{3w}{\varepsilon_r(r - 2d - w)^3}}
\]

(4.3)

where \( \varepsilon_r \) is relative permittivity of the substrate, \( w \) is slot ring width, \( d \) is the gap between two ring slot.
Figure 4.3 shows the simulated & measured return loss of the dual-element MIMO antenna system and good agreement between the measurement and simulation is found. From the outcomes, two operating bands nearly at 2.36GHz and 3.43GHz are appeared with good impedance matching. The measured -10 dB impedance bandwidths for return loss reach 0.44GHz (2.29–2.43 GHz) and 0.38 GHz (3.27–3.65 GHz) in two distinct operating bands respectively, which can cover desired LTE 2300 MHz and 3.5 GHz WiMAX bands. On the other hand, the peak isolation is just about dB at 2.36GHz and -8 dB at 3.43GHz. The reason for low isolation in both operating bands without utilizing any decoupling unit is because of the current reversal between two antennas. The current distributions at 2.4 and 3.5 GHz are numerically shown in figure 4.4. It is found that the current mainly intensified on the interior CSRR at 2.4 GHz, whereas at 3.5 GHz, the current focused on the external SRSR. This demonstrates that the lower and upper operating frequencies of the antenna are furnished by the CSRR and SRSR correspondingly, as per numerical prediction.

To reduce the mutual coupling between the two antennas in both the bands, a periodic metamaterial decoupling structure is intended to introduce a wide band-gap at 2.4 GHz & 3.5 GHz which are the proposed antenna's working frequency. Accordingly, mutual coupling between two radiating units anticipated that would reduce.
Metamaterials based Miniaturized Planar Antenna Design

4.2.3 Design and Characterization of CSR2S

The Mutual coupling reduction in dual-band dual-element MIMO antenna system is achieved by introducing periodic Complementary metamaterial (MTM) unit cells as decoupling structure between two antenna elements. Here, we have used MTM based complementary two-turn spiral resonator (CSR2) structure [42] to construct the unit cell for wideband filter with wide band-gap characteristics and compact size (Fig. 4.5). Compared with the conventional complementary split ring resonator, the CSR2 provide a better method for miniaturization [42].

FIT based 3D simulator being utilized to examine the influence of the CSR2 on the antenna’s performance. The dimension of the CSR2 MTM unit cell is optimized to obtain stop-band filtering characteristics from 2.25 to 3.65 GHz. The optimized dimensions of CSR2 are as follows: \( l=4.3 \text{mm}, \ w_1=c_1=0.5\text{mm}, \ s=0.7\text{mm} \). The gap distance \( (P_g) \) between two CSR2 unit cells is 0.6 mm. The transient domain solver is used to simulate CSR2 unit cell structure with periodic boundary condition in CST MWS to demonstrate the stop-band filtering characteristics.
The corresponding 1-D dispersion diagram for CSR2 MTM unit cell structure is shown in Fig. 4.6. It is calculated by substituting S-parameters, which are derived with EM simulation tool, in Equation 4 as follows [43]:

$$\beta_p = \cos^{-1}\left(\frac{1 - S_{11}S_{22} + S_{12}S_{21}}{S_{21}}\right)$$

(4.4)

where \( p \) is the periodicity of the periodic unit cell = length of the CSR2 unit cell (\( l \)).

A Strong rejection characteristic is evident in the 2.25 GHz– 3.65 GHz band in the dispersion diagram. It is found that the \( \beta-p \) versus frequency variation is almost zero, and there is flat wide stop-band is visible within the desired band.

![Figure 4.5: CSR2 unit cell.](image)

![Figure 4.6: Dispersion diagram for (2×3) periodic CSR2 MTM unit cells.](image)
4.2.4 MIMO System with Decoupling Structure Design and Performance Discussion

Based on the optimal dimensions, a model of the dual frequency MIMO antenna system with 2×3 periodic MTM based CSR2 decoupling structure in the ground plane has been designed, fabricated, and experimentally investigated.

![Figure 4.7: Geometry for the dual-band dual-element MIMO antenna system with 2×3 CSR2 slots.](image1)

Figure 4.7 and figure 4.8 show the geometrical configuration and the image of the fabricated prototype. The antenna elements are fed by 50Ω SMA connectors. The simulated & measured endorsement of the MIMO antenna system have been depicted in figure 4.9, which shows the $S_{11}$ and $S_{21}$ amongst the two antenna units with and without utilizing the periodic CSR2s decoupling structure, which exhibits the reflection coefficient and coupling isolation between the two antennas with and without utilizing the periodic CSR2s decoupling unit.
The prototype is measured using Agilent N5230D vector network analyzer (VNA). Since both the elements are symmetric, only $|S_{11}|$ and $|S_{21}|$ are calculated.

It is verified from the simulation outcomes, the resonant frequency of the MIMO antenna system with MTM based CSR2 decoupling structure is slightly shifted from 2.36 GHz to 2.43GHz in the lower band and from 3.43 GHz to 3.49GHz in the higher band. This shift was because of the CSR2 structure located between the two antennas, which influence the fringing field between the two slot antenna which can influence the antenna's element electrical size and consequently the resonance frequency.

![Figure 4.9: S-Parameter results of dual-element MIMO antenna system with CSR2s decoupling structure: (a) $S_{11}$; (b) $S_{21}$.](image)

The simulated result shows that the dual-element MIMO antenna with CSR2s decoupling structure is resonating at 2.43 & 3.49 GHz effectively, at which the $S_{11}$ is better than -30 dB at peak resonating frequencies with -10dB impedance bandwidth (BW) equal to 150 MHz from 2.32 to 2.47 GHz and 290MHz from 3.34GHz to 3.63GHz for the two frequency bands, approximately. By using MTM based CSR2 decoupling structure between the two antenna elements, The minimum simulated antenna isolation in the lower band is nearly -32 dB, while in the upper band it is lower than -23dB (figure 4.9). Introducing decoupling structure between two antenna elements, there is an improvement of 16 dB antenna isolation in the lower band, and 15dB antenna isolation in the higher band is found in the simulated result by acting as a wideband band-notch filter.
From measurement results, it is confirmed that the designed prototype antenna resonates at 2.44 GHz & 3.50 GHz effectively, with return loss less than -20 dB and -10 dB impedance BW up to 130 MHz ranging from 2.34 to 2.47 GHz and 290 MHz from 3.35 GHz to 3.64 GHz respectively. By using 2 x 3 array CSR2s MTM band-stop filtering structure between two metamaterial inspired antenna elements, the measured isolation becomes less than -32 dB in lower band (2.34-2.47 GHz) and -18 dB in the higher band (3.35-3.64 GHz). So in other words, the CSR2s decoupling structure reduced the antenna coupling nearly 15 dB in the lower band and 10 dB in the higher band. Hence, there is a good concurrence amongst simulated and measured outcomes. However, a little frequency alter between them can be seen. The discrepancy between them was probably due to the fabrications and the loss at the connectors. The measured -10 dB impedance BW can cover the desired LTE 2300 MHz and 3.5 GHz WiMAX band. The antenna radiation patterns are computed by exciting one of the antennas and loading the other with 50Ω impedance. The normalized measured radiation patterns of the designed MIMO antenna system in the E-plane and H-plane at 2.4 GHz and 3.5 GHz are shown in figure 4.10. The normalized radiation patterns in the E-plane and H-plane for the lower and upper frequency band are doughnut-shaped.

![Normalized radiation patterns](image-url)
The measured directivity of the MIMO system with CSR2 decoupling structure is shown in figure 4.11. It can be observed that the peak measured directivity of the antenna is about 3.9 dBi in the low-band (2.34 GHz–2.47GHz), and about 4.2 dBi in the high-band (3.35 GHz-3.64 GHz) respectively.

![Graph](image)

**Figure 4.11:** The peak measured gain plot of purposed MIMO antenna system.

The magnitudes of the E-field of the MIMO antenna system with & without the MTM based CSR2s unit at different working bands (2.4 & 3.5 GHz) are depicted in figures 4.12 & 4.13 respectively, in which the E-field distribution on the ground plane, while one antenna is energized while the another antenna is ended with a matched impedance. Devoid of the CSR2s decoupling structure, high focused surface currents is observed in the radiating antenna that causes strong E-field coupling due to surface waves overlapping. The inclusion of CSR2s between the two antennas on the ground plane of the MIMO antenna system improves the coupling isolation significantly. Specifically, at 2.4 & 3.5 GHz the coupling is emphatically suppressed by (2×2) array CSR2 band notch decoupling structure.
Envelope correlation coefficient (ECC) is a critical constraint to quantify the diversity performance of a MIMO framework and can be achieved from the measured S-parameters. A low ECC expedite high diversity [44]. For a dual-element antenna system, ECC can be defined using [45], which is shown in Equation 4.5.

\[
ECC = \frac{|S_{11}^*S_{21} + S_{21}^*S_{22}|^2}{[1 - (|S_{11}|^2 + |S_{21}|^2)][1 - (|S_{11}|^2 + |S_{21}|^2)]}
\]

(4.5)
The simulated and measured ECC evaluated from S-parameters are compared in figure 4.14. A good agreement has been realized. The measured ECC values of the designed MIMO system at both frequency band of operation were below 0.1 that implies that the MIMO system has excellent diversity at the desired dual working bands.

The Total efficiency ($\eta_{\text{tot}}$) is another important parameter to additionally investigate the performance of MIMO system [46], in addition to mutual coupling and ECC performance. 

$$\eta_{\text{tot}} = \eta_{\text{rad}} (1 - |S_{11}|^2 - |S_{21}|^2) \quad (4.6)$$

Figure 4.15: Differences between simulated and measured total efficiency of the MIMO antenna.
The total efficiency ($\eta_{tot}$) of the designed MIMO antenna system is evaluated utilizing Equation 4.6, $\eta_{rad}$ represents the radiation efficiency considering the dielectric and conducting losses into account. The measured $\eta_{tot}$ of the designed dual-band MIMO system has been shown in Fig. 4.15, from which it can be seen that the measured efficiency is more than 75% in both the desired working bands.

Table 4.1 compares the performance (in terms of overall dimension of the antenna, distance between antenna elements and isolation improvement) of the proposed configuration to other dual element MIMO systems that showed up in the literature. The table shows the dual band with compact size and high isolation between antennas are the main operational advantage of our design. The compact size of the designed dual-element MIMO antenna system will permit fitting inside the size of most modern wireless system.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Frequency band (GHz)</th>
<th>MIMO Antenna Size (mm$^2$)</th>
<th>Edge-to-edge spacing (mm)</th>
<th>Improvement in $S_{21}$(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2.4</td>
<td>30×70</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>1.5</td>
<td>50×17</td>
<td>26</td>
<td>15(Lower Band) &amp; 20(Higher band)</td>
</tr>
<tr>
<td></td>
<td>2.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>.770</td>
<td>58×110</td>
<td>16</td>
<td>10(Lower band) &amp; 12 (Higher band)</td>
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<tr>
<td></td>
<td>2.38</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>0.755</td>
<td>50×100</td>
<td>16</td>
<td>10dB (Lower band) 2dB (Higher band)</td>
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<td></td>
<td></td>
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</tr>
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### Table

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Frequency band (GHz)</th>
<th>MIMO Antenna Size (mm²)</th>
<th>Edge-to-edge spacing (mm)</th>
<th>Improvement in $S_{21}$(dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>5.4</td>
<td>110×54</td>
<td>18 $(0.32\lambda_0)$ at 5.4 GHz and $(0.4\lambda_0)$ at 6.8 GHz</td>
<td>5 to 10</td>
</tr>
<tr>
<td></td>
<td>6.8</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>2.4</td>
<td>38×43</td>
<td>14</td>
<td>Not reported</td>
</tr>
<tr>
<td></td>
<td>5.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>2.5</td>
<td>70×40</td>
<td>29</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proposed</td>
<td>2.4</td>
<td>43×26</td>
<td>10</td>
<td>15dB (Lower band)</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td></td>
<td></td>
<td>10dB (Higher band)</td>
</tr>
</tbody>
</table>

### 4.2.5 Conclusion

In this section of the chapter, a compact dual-band dual-element MIMO antenna system based on metamaterial for LTE 2300 and WiMAX applications has been designed and physically realized. The antenna element consists of a SRR encircling a CSRR. Dual band mutual coupling is obtained by using a 2×3 periodic MTM based CSR2 decoupling unit within two antenna array. It was examined that the designed dual-element MIMO system has dual working bands ranging from 2.34 GHz to 2.47GHz in the lower band and from 3.35GHz to 3.64GHz in the upper band. The measured isolation is nearly -32 dB and -18dB in the lower and higher frequency bands. Low correlation coefficient values in both bands of operation indicate a high diversity gain for the MIMO antenna system.
SECTION B

4.3 A Compact Miniaturized Tri-band Circular Patch Antenna Loaded with Metamaterials

4.3.1 Introduction

With the rapid advancement of modern communication systems, the interest for designing low profile and multi-frequency antennas is attractive for wireless terminals. The challenges, however, include low profile, miniaturization, and integration with RF circuits [47].

Recently, engineered materials such as metamaterial (MTMs) offer an intangible direction for realizing miniaturize antennas with good performance which likewise provide a reasonable route to double or multi mode operations reported in [48-49]. It mainly focuses on miniaturization, better radiation performance.

Electrically small resonant rectangular patch antennas using split ring resonators (SRRs) and its dual counterparts called complementary SRRs (CSRRs) metamaterial unit cells have received much attention in the design dual and multi-band small antennas in microwave regime.

Dual-band small resonating antennas were investigated [50-53] by loading CSSR MTM unit cells either on the ground plane or radiating surface. But by etching CSRR unit cells in the ground plane or from radiator surface, the gain and efficiency of such antennas degrades considerably because of the introducing of loss by the complementary split ring resonator unit cell at the resonant frequency simulated by the MTM CSRR unit cell. Later, it was concluded that the most of these electrically small size MPA with metamaterial loading act as a resonators but not as a good radiators. However, it has been seen that the radiation performances like gain and directivity of similar miniaturized resonant antennas degrade seriously due to the decrease of overall electrical length.
To increase the gain of the MPA, Xie et al. and his group realized numerically and experimentally a new dual or multi mode antenna achieved by etching the ground plane of planar antenna with two or more complementary split ring resonators [54]. Later, several miniature resonant planar antennas have been successfully demonstrated to show dual-mode operation with enhanced directivity gain performance by using two or more complementary split ring resonator DGS structure. but, these antennas need large overall dimension to implement practically [55-56].

Even as vast majority of the proposed approaches that cited in the research articles demonstrate a single or dual operating band for metamaterial based small antenna. This clearly negates to the development of next generation wireless communication systems, of which multi frequency applications have turned out to be crucial. Multi-mode antennas incorporating with CSRR have been proposed [57-59].

In this section, inspired by the reported literatures, a compact tri-band circular patch antenna(CPA) embedded with a pair of low loss complementary skewed omega resonator (CSOR) MTM unit cells on the ground plane has been investigated. Beside miniaturization, this proposed work mainly focuses on multiband operation with performance enhancement of the circular patch antenna.

The designed antenna operates at three operating frequencies (2.4 and 5.8 GHz and 7.8GHz) effectively. The simulated results are compared with measured result. The developed antenna has sample in geometry, occupied smaller area. It shows good impedance matching and achieved moderate gain at the desired operating bands.

4.3.2 Antenna Configuration

The configuration with multiband CPA loaded with metamaterial resonators has been depicted in figure 4.16. It is based on circular patch loaded with two symmetrical complementary skewed omega resonators (CSORs) MTM unit cell. This would excite the circular patch as being placed on a double positive material and single negative material (DPS-SNG) medium and fed at the positive side.
Figure 4.16: Configuration of the tri-band antenna embedded with dual CTORs.

The CSORs are introduced in the ground plane along the radiating edges and at a distance of ‘$dx$’ away from the centre of transmission feed line. A progression of parametric examination has been done to locate the best position of CSRR in $x$- and $y$- directions from the centre, at which better impedance matching, radiation efficiency and gain in all the desired bands can be achieved.

The metamaterial loaded multi-band CPA has been designed on a glass epoxy (FR4) substrate with dielectric constant ($\varepsilon_r$) = 4.4, thickness ($h$) = 1.6 mm, and loss tangent ($\tan \delta$) = 0.02.

The design process starts with a basic circular patch operating at 5.05 GHz TM$_{01}$ fundamental frequency mode. The geometrical parameter of the CPA is determined from the following equations [60].

$$a = \frac{F}{\{1 + \frac{2h}{\pi\varepsilon_r F} \left[\ln \left(\frac{\pi F}{2h}\right) + 1.7726\right]\}^{\frac{1}{2}}}$$  \hspace{1cm} (4.7)

where

$$F = \frac{8.7911 \times 10^9}{f_r\sqrt{\varepsilon_r}}$$  \hspace{1cm} (4.8)
where $f_r$ is the resonating frequency, $h$ is substrate thickness in mm, $\varepsilon_r$ is relative dielectric constant of dielectric substrate. The final optimized design parameters of the multi mode CPA are given in Table 4.2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$R$</th>
<th>$d_y$</th>
<th>$P$</th>
<th>$W$</th>
<th>$L$</th>
<th>$W_f$</th>
<th>$L_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension (in mm)</td>
<td>21</td>
<td>4.6</td>
<td>2</td>
<td>27</td>
<td>30</td>
<td>1.92</td>
<td>13</td>
</tr>
</tbody>
</table>

### 4.3.3 Design and Characterization of CSOR MTM Unit Cell

Here, in this section, the electromagnetic characteristics and electric resonance frequency behaviour of a low loss complementary skewed omega resonator (CSOR) MTM unit cell structure have been discussed. Compared with conventional CSRRR structure, the CSOR metamaterial unit cell provides a better method of miniaturization with very low loss and dual-band negative permittivity characteristics in microwave frequency regime [61]. It is also found that the skewed omega dual band resonator structure is further compacted compared to the existing electric resonators utilized to attain negative permittivity property in dual frequency regime.

![Figure 4.17: Magnitude & phase of S-parameter of MTM unit cell.](image)
To find out its resonating uniqueness property and retrieve the constitutive parameter (permittivity) of the metamaterial unit cell through EM simulation, a waveguide set up with infinite periodic boundary condition is used. Figure 4.17 show the geometrical configuration of CSOR. It provides negative permittivity characteristics at the desired frequency when excited with tangential electric field. The complete geometrical parameters of the CSOR are listed in Table 4.3. A perfect electric conductor (PEC) and perfect magnetic conductor (PMC) boundary conditions are assigned along x-axis and y-axis. The medium perpendicular to the z-axis is modeled as the input/output ports. Then, the CSOR is excited by an EM wave propagating along z-axis with electric field vector (E) along the x-axis and magnetic field vector (H) along y-axis, as depicts in figure 4.17. The approximate resonance frequency of CSOR can be calculated by using [62].

The simulated S-parameter of CSOR unit cell is shown in Figure 4.18. The spectral position of the resonating frequencies can be evaluated from the spectral location of the transmission minimum. It has been found that, there are two pass-bands with reflection dips occurring at 3.86 and 6.8GHz respectively, where the electric resonances occurred nearby. The transmission peaks are nearly 0 dB and −1.01 dB level in the 1st and 2nd band respectively, and the reflection spectral power is around -20 dB at the peak resonating frequency of the first band while it is better than -50 dB in the second band.

Table 4.3: CSOR MTM unit cell dimension.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>a</th>
<th>c</th>
<th>d</th>
<th>g</th>
<th>ax</th>
<th>ay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
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<td>0.4</td>
<td>0.9</td>
<td>0.5</td>
<td>8.8</td>
<td>6.1</td>
</tr>
</tbody>
</table>

The effective medium parameters of the designed complementary skewed omega resonator unit cell are calculated from the simulated Scattering parameters obtained from numerical analysis, using the regular NRW procedure [63]. It is found that from 3.57 to 4.07 GHz and from 6.6 to 8.0GHz, the CSOR medium give negative permittivity (near the electric resonance of CSOR MTM unit cell) and the unit cell behave as SNG medium in these dual operating frequency range.
4.3.4 Results and Discussion

The designed multi mode CPA is investigated by utilizing FEM based 3D EM solver. The comparison between simulated reflection coefficients of the CPA loaded with and without CSOR is depicted in figure 4.20. It is evident that the conventional antenna resonated at 5.1GHz effectively with minimum reflection coefficient of -32dB at the peak resonating frequency.
Figure 4.20: Simulated reflection coefficient ($S_{11}$) of CPA embedded with and without and CSORs

Figure 4.21 shows the co-plane radiation characteristics for E-plane and H-plane of the simple CPA without CSRR. The measure gain of the conventional antenna was 6.2dBi.

Figure 4.21: Simulated radiation pattern of the conventional CPA at 5.1GHz.
To generate tri-band, the conventional CPA was loaded with a pair of CSRRs in the ground plane. The prototype of the tri-band antenna is shown in figure 4.22. The return loss ($S_{11}$) of the fabricated antenna is tested using Agilent 8719 VNA.

![Figure 4.22: Simulated and measured $S_{11}$ of CPA with and without CSRRs loading.](image)

The comparison between simulated and measured $S_{11}$ of both the antennas have been depicted in Figure 4.22, which are in good agreement. With the presentation of CSRRs in the ground plane, tri-band frequency operations are occurred at 3.86GHz, 5.25GHz and 6.728GHz respectively. The measured -10 dB impedance bandwidths are about 90 MHz for the 3.86 GHz (from 3.81 to 3.92 GHz); 100 MHz for the 5.25GHz (from 5.20 to 3.30 GHz); and 80 MHz for the 6.72 GHz (from 6.67 to 6.75 GHz).
In the designed tri-band antenna, the top layer circular radiating patch excites the 2nd resonant frequency (5GHz), whose resonance frequency can be determined from equation (1). From the numerical analysis using EM tool, it is evident that by loading of the CSRRs to the patch slightly shifted the fundamental resonant frequency of the circular radiating patch (2nd resonating frequency) from 5.06 GHz to 5.243GHz. This shift of the resonating frequency to a higher value was because of the introduction of the CSOR metamaterial electric al resonator which influence the fringing field of the patch which can reduce the antenna’s actual dimension and hence the operating frequency shifted to a little higher frequency. Hence, it suggests reduction in the radiating patch size. Whereas, CSORs are responsible for 1st and 3rd resonance frequency bands. Electrical resonance characteristics of the CSRR are used to generate the 1st and 3rd resonance frequencies at 2.4GHz and 7.6GHz respectively. The measured results demonstrated our proposed tri-band antenna design in that each of the bands is controlled by CSRR.

The simulated and measured far-field radiation patterns of CPA loaded with and without CSRR in the ground plane in E-plane and H-plane for 2.4, 5.1 and 7.2 GHz bands are revealed in figure 4.23 [a-c] respectively. It is evident that there is a good agreement between simulated and measurement radiation pattern result. As shown both the results provide nearly omni-directional radiation pattern in H-plane and bi-directional radiation pattern in E-plane.
To enable a clear understanding of the working operating bands, the E-field distribution of the conventional CPA and proposed CPA loaded with CSRRs at the desired operating frequencies are depicted in figure 4.25 and figure 4.26 respectively.

It is observed that for the conventional CPA the maximum current at 5GHz is mainly focused on the radiating patch (Figure 4.22). Whereas in case of proposed CSRR etched CPA; the current distribution at 5GHz is re-arranged and of the major current is mainly concentrated on the radiating patch and small portion of the current focus near the CSRRs in the ground plane, which reveals that the CSRR has a certain capacitive
coupling effect on the radiating patch. Hence this resonating frequency center (at 5.06 GHz) is little higher than that of without CSRR. It is observed that the 1st and 3rd resonance frequency bands (2.4GHz and 7.05 GHz), the current focused on the CSRRs.

Figure 4.26: Surface current distribution of the CSORs loaded CPA on patch (left) and on ground (right) at: (a) 3.85 GHz, (b) 5.25 GHz and (c) 6.7GHz.
4.4 Chapter Summary

In this chapter, different planar dual and tri band metamaterial inspired miniaturized resonating antennas by partially loading on the substrate, and on the ground plane have been studied, designed and investigated the characteristics numerically and experimentally.

In the first part, a compact dual-band MTM based antenna for MIMO system has been investigated. The dual-band antenna element has been employed to develop a two-element MIMO system with reduced mutual coupling for LTE 2300 and WiMAX applications. The antenna element consists of a SRSR encircling a CSRR. Dual-band coupling reduction is realized by employing a 2×3 array of metamaterial based CSR2 structure between two antenna arrays in MIMO system. It was confirmed that the designed dual-element MIMO system has dual BWs operating from 2.34 GHz to 2.47 GHz and 3.35 GHz to 3.64 GHz in the lower and upper frequency regime. The measured isolation is nearly -32 dB and -18 dB for lower and higher operations. Low correlation coefficient values in both bands of operation indicate a high diversity gain for the MIMO antenna system. Further, it shows good radiation properties and steady directivity over the entire operating bands. The designed antenna is appropriate for cutting edge wireless devices with smaller size.

In the last section of the chapter, a metamaterial inspired antenna has been explained. Here, a novel electrical small tri-band circular patch antenna (CPA) has been presented. The proposed tri-band CPA is based on metamaterial structure called complementary skewed omega type resonator (CSOR). The conventional CPA operating with 5.1GHz loaded with a pair of symmetric CSORs on the ground plane excite three working frequencies. The proposed antenna operates at 3.86Gz, 5.25GHz and 6.728GHz respectively with compact size of 27×30×1.6 mm³. Numerical simulation of the designed antenna shows that the operating frequencies of each band can be modulating separately. A better matching, omni directional radiation properties with steady gain over the each working bands was realized. A good conformity between measurement and simulations outcomes approves the design approach.
REFERENCES


Metamaterials based Miniaturized Planar Antenna Design


