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

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Abstract
An aperture coupled two element metamaterial antenna suitable for multiple input multiple output applications in the frequency band of 7.525–9.1 GHz is proposed. This three-layered structure utilizes a vertical array of rectangular complementary split ring resonators between the contiguously placed circular non-bianisotropic complementary split ring resonator radiating elements for enhancement of isolation. This antenna achieves a maximum of 47 dB isolation through this Mu Negative structure insertion in the frequency band for 0.11 λ₀ separation of the two antenna elements. The proposed antenna achieves a fractional −10 dB impedance bandwidth of 18.94% and has a peak gain of 8.15 dB. 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 λ₀ × 0.45 λ₀ × 0.133 λ₀ and is suitable for X-band military applications.

Keywords Metamaterial · Split ring resonator · MIMO · Aperture coupling · Isolation

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. A MIMO antenna has two or more antenna elements in it. These elemental antennas are integrated along with proper MTM structures to achieve a good degree of mutual coupling suppression. With the prevalent Internet of Things (IoT) technology, very high data rate is the paramount requirement under 5G communications. Whenever the user data rate requirement is high, MIMO antennas come handy.

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). One of the main concerns in MIMO antenna design is reduction of mutual coupling between constituent MIMO antenna elements. Suppression of these interfering signals from MIMO antenna elements in addition to other noise signals is addressed through this parameter Signal-Interference-Noise Ratio (SINR). It is defined as the power of a certain signal of interest divided by the sum of the interference power from all the other interfering signals and power of some background noise. It is a quantity used to give theoretical upper bounds on channel capacity [1] i.e. the data rate transfer in wireless communication systems.

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. Channel capacity can be increased in orders of ten in massive MIMO systems [2], if aggressive spatial multiplexing is used. While these exotic fictitious 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. Operating bands of Market existing MIMO antenna systems include WLAN, WiMAX, Long Term Evolution (LTE), Defence system bands.

1.1 Related Works

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 [3, 4]. Since mutual coupling suppression down to the levels of $-30 \, \text{dB}$ 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 $-46.5 \, \text{dB}$ levels have been reported in the literature [5]. The impact of MTM on antenna system designs is phenomenal [6–9]. 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 [4, 10]. Two closely spaced meander line antennas are effectively decoupled through an MTM substrate and this antenna system is reported to achieve an isolation of $12–19 \, \text{dB}$ over $5.1–5.9 \, \text{GHz}$ frequency band [3]. This simple design offers improved impedance matching and gain. Unwanted frequency bands are notched for reducing
multipath fading effects in four element Ultra Wide Band (UWB) MIMO antenna system [11] and envelope correlation coefficient (ECC) of less than 0.02 is maintained across the operating frequency band [12].

An MTM mushroom wall has been used to improve isolation in a four element MIMO antenna system [13]. 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 42 dB with an envelope correlation coefficient well below 0.02 within the operational band of 2.39–2.45 GHz. 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 –30 dB level [14]. 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 × 2 arrays. As the number of elements in an array antenna increases, the patch patterns on the ADS become very complicated [15].

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 –30 dB 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 [16]. Mutual coupling reduction in Dielectric Resonator antennas useful for 60 GHz MIMO system has been attained through a metasurface shield [5]. The constructed prototype achieved mutual coupling levels of −30 to −46.5 dB in the 59.3–64.8 GHz frequency band.

A MIMO antenna system employing a frequency selective surface (FSS) wall has been reported to achieve −30 dB isolation levels [17]. The FSS walls of this system were optimized for the operating band of 57–63 GHz to achieve this level which is a thumb-rule requirement in a MIMO system [15]. 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 5 × 10⁻⁶ 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 30 GHz employing crossed-dipole structures on the FSS has been reported [18] 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 55 dB isolation was achieved at a centre frequency of 3.3 GHz. 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 [20]. A self-diplexing MIMO antenna improving the isolation has been reported [21, 22]. In this paper a dual element antenna system is proposed for MIMO applications in the frequency band of 7.525–9.1 GHz. Any MTM antenna design requires a radiating patch. Here in the present design of the antenna, instead of a simple circular (or any other MTM) patch, NBCSRR has been used as a radiating patch to improve the bandwidth of the MIMO antenna [23].
To reduce the mutual coupling an MTM array is inserted in between two NBCSRR radiating elements. In a dielectric slab, the permittivity $\varepsilon$ and permeability $\mu$ are tensors, in general. A set of new possibilities arises from the cross terms. That is, the magnetic dipoles excited not only by the magnetic field but also by the electric field. Similarly, the electric dipoles excited not only by the electric field but also by the magnetic field. These cross terms lead to the case of bianisotropy when the dipole vectors are oriented perpendicular to the exciting fields. And the case of chirality arises when the dipole vectors are oriented parallel to the exciting fields. These cross polarization terms cancel out in complementary SRR structures leading to zero bianisotropy term $\xi$ and the CSRR structure is nonbianisotropic. 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 $\tan\delta=0.002$ 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.

As shown in Figure 2, the NBCSRR is loaded onto the circular patch of radius $r_1 = 4.9$ mm which has been considered as the outer ring and the inner ring radius is $r_4 = 1.7$ mm. In this complementary design, the width of each circular strip is $S_1 = 0.8$ mm and the split gap is $g = 0.8$ mm to make proper resonance. This NBCSRR radiating element is printed on a 1.6 mm thick FR4 epoxy substrate with a width of $W = 16$ mm and length of $L=16$ mm. A microstrip line with a width $W_s = 2$ mm, length $L_s = 10$ mm and stub length $S = 4$ mm has been printed on one side of the bottom substrate. Printed on the other side of the bottom substrate is the aperture of width $S_w = 1.3$ mm and length $S_l = 8$ mm.

The antenna resonant frequency of 8.5GHz for X-band applications has been decided based on Eq. (1) [24].

![Circular patch antenna A and MTM loaded antenna B](image)
where \( r_1 \) is the radius of the outer ring, \( r_4 \) is the radius of the inner ring, \( w = S_1 = 0.8 \) mm is the width of the ring, \( \varepsilon_r = 4.4 \) is the relative permittivity and \( c = 3 \times 10^8 \) m/s is the velocity of light.

### 2.1 Realization of MTM Characteristics

The NBCSRR-MTM unit cell simulation has been carried out by using HFSS to get the values of reflection coefficient \( (S_{11}) \) and transmission coefficient \( (S_{21}) \). Using these S-parameter values the real and imaginary parts of the permittivity \( (\varepsilon) \) have been extracted following the procedure outlined in [25]. The permittivity of the MTM unit cell is given by

\[
\varepsilon = n/z
\]

where

\[
n = \frac{1}{k d} \cos^{-1} \left[ \frac{1}{2S_{21}} \left( 1 - S_{12}^2 + S_{21}^2 \right) \right]
\]

and

\[
z = \sqrt{\frac{(1 + S_{11})^2 - S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}}
\]

MATLAB code was written and used in the retrieval of the real and imaginary parts of \( \varepsilon \) values. Figure 3 shows that a sharp transition from positive to negative regime at the resonant frequency occurs in the real part of epsilon confirming the epsilon negative nature of the NBCSRR-MTM structure.

### 2.2 Schematic of Aperture Coupling

Depicted in Fig. 4 is a comprehensive picture of the aperture coupling realized in the present design of an all MTM MIMO. Our MIMO antenna has two antenna elements. The
3D view of one element is depicted in Fig. 4 and its geometry and how the parts of this antenna element are printed on FR4 epoxy are clearly explained below.

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 8 mm × 1.3 mm 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.

Aperture coupled antenna feed technique includes electrically isolated microstrip lines and radiating elements. In our design the radiating element and the microstrip line are electromagnetically coupled through a small rectangular aperture in the isolating ground plane.

2.3 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 30 mm × 16 mm × 4.7 mm. The antenna is excited through the bottom edge of the microstrip line and is powered up through an SMA connector. SMA connector is a sub-miniature coaxial cable connector and its name is extracted from the phrase Sub-Miniature A. It is often used for providing RF connectivity within boards and many microwave components use it. Male and female SMA connectors are designed to have standard 50 Ω impedance across them and different manufacturers bring them out in different specifications and types.

As shown in Figure 5, in antennas C and D an additional antenna element is printed to realize the MIMO antenna design. Two NBCSRR elements of outer ring radii \( r_1 = 4.9 \) mm with a distance of separation of the order of \( \lambda_0/8.3 \) (4 mm) are printed on the superstrate of
FR4-epoxy with lateral dimensions $L_a = 16$ mm, $W_a = 30$ mm and thickness 1.6 mm. The dimensions of the substrate containing ground, aperture ($S_w \times S_l = 1.3$ mm$\times$8 mm) and the microstrip feedlines ($W_s = 2$ mm) are also the same. An air gap of around 1.5 mm has been maintained between the superstrate and the substrate to achieve a gain of 8.15 dB at the resonant frequency of 8.5 GHz.

Though the MTM radiating elements loaded in antenna D are self diplexing (A self-diplexing antenna achieves good isolation between the antenna elements without the aid of any additional MTM structure), mutual coupling is greatly reduced only after inserting the
rectangular vertical MTM array in between the two radiating elements as shown in Fig. 6. In Fig. 6, the two NBCSRR radiating elements are placed contiguously on the FR4 substrate with a centre to centre distance of D = 8.9 mm and the edge to edge distance between the same is d = 4 mm. Five rectangular CSRRs of dimensions 3 mm x 2.7 mm are used in constructing the vertical array that has been used for the purpose of mutual coupling suppression.

All the characteristics of the antenna are simulated through finite element based High Frequency Structure Simulator (HFSS). High Frequency Structure Simulator (HFSS) is one among the several commercial tools used for antenna design and the design of complex microwave circuit elements such as filters, absorbers etc. It is an industry standard software to simulate 3-D full wave electromagnetic fields, brought out by the company Ansys inc.

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 7 shows that the resonant frequency shifts in the direction of positive x values as the air gap height h value increases from zero. At the value of 1.5 mm of h, the antenna achieves a gain of 8.15 dB as depicted in Fig. 13a with a bandwidth of about 1.575GHz. This prompted us to decide upon the optimized value of h = 1.5 mm.

3.2 Stub Length S Optimization

The stub length is one of the main components to effect improvement in the return loss. Stub length is the length after the feed line in the present design. Its purpose is to tune the excess reactance of the aperture. The length of the stub can be varied to achieve a
reactance compensation for matching purposes in the antenna design. The open stub length can be adjusted to get the required reactance. Typically stub length is of the order of 0.5 times the guided wavelength. The plots of return loss against frequency for various stub lengths have been provided in Fig. 8. Stub length $S$ improves the return loss about $-40$ dB in its 4 mm value at the resonant frequency of 8.5 GHz while effecting insignificant variation in its other values, viz. 3 mm, 3.5 mm, 4.5 mm and 5 mm, as depicted in Fig. 8. Hence the optimized stub length value has been taken as $S = 4$ mm.

3.3 Aperture Length $S_1$ Optimization

Aperture length $S_1$ is one of the major elements in this type of antenna to stimulate the radiating element. Aperture length optimization is done the following way. Starting from an $S_1$ value of 7 mm, it has been varied in steps of 0.5 mm up to 9 mm. At
3.4 Antenna Fabrication

After the optimization of the parameters, an antenna prototype has been fabricated which is shown in Fig. 10. Fabrication of the prototype had been effected using Printed Circuit Board (PCB) technology. 0.03 mm thick copper strips have been printed on the FR4 substrate as per the design parameters.

\[ S_1 = 8 \text{ mm} \] the antenna exhibited the best return loss characteristics (Fig. 9) and this value has been decided upon as the optimum value for \( S_1 \).
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. 11. The proposed MIMO antenna is resonating at 8.5 GHz (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 – 10 dB impedance bandwidth of 18.94% in the frequency range of 7.525–9.1 GHz.

4.1 S-Parameters

The measured and simulated S-parameters of the antennas are presented in Fig. 12. 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 47 dB in between the measured values of S11 and S21 in the operating frequency band.

4.2 Gain and Efficiency

Figure 13a shows that the gain is gradually increasing when the air gap value increases from zero to 1.5 mm. At zero-air gap, a gain of 3 dB is maintained through the bandwidth. It has been increased up to 8.15 dB when the air gap is kept at 1.5 mm. 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 to 81.14% when the air gap is varied from 0 to 1.5 mm. Iteration of antenna gain and efficiency are depicted in Figure 13a and b.
4.3 Radiation Patterns

Simulated and measured radiation patterns of the proposed antenna for the targeted frequency is given in Figure 14. 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. Fairly good agreement between the measured and simulated values is evident from the radiation patterns. The slight discrepancy could be due to the fabrication tolerance.

4.4 Transmission Coefficient

The simulated and measured results of the transmission coefficients are presented in Fig. 15. It is clear from the profiles that the antennas C to E achieve an isolation of up to 47 dB in the operating frequency band. Besides, it is clear that the measured $S_{21}$ values of antenna E do curve similar to the simulated values. From the curves, it is obvious that MTM loaded antenna D has self-diplexing capability.

4.5 Envelope correlation Coefficient

Isolation is an important parameter of MIMO antenna which can be measured from ECC value. The Envelope Correlation Coefficient is defined as the average correlation between the total radiated power within 3-D space. Its value will be zero ideally. It is an important parameter in evaluating antenna diversity performance to increase the efficiency of antenna array systems.

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 in Eq. 5 [17].
From Fig. 16, the fabricated prototype maintains an ECC of 0.015 over the resonant frequency of 8.5 GHz. The ECC value over the targeted frequency band is less than 0.025. Performance comparison of our antenna with previous works is given in Table 2. Expansion of abbreviations have been used in this paper are presented in Table 3.
Fig. 14 Simulated and measured radiation patterns of the antenna (a) E-Plane and (b) H-Plane
5 Conclusions

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 role to suppress the mutual coupling. Mutual coupling suppression procedures in most of the existing systems led to significant reduction in bandwidth. This drawback is eliminated in our MIMO antenna. This apart the present antenna is low-profile and provides better efficiency and gain. Measured values show that an isolation of nearly 47 dB is achieved with the decoupling technique in the operating frequency band of 7.525–9.1 GHz. This antenna is most suitable for X-band military applications.
| Ref  | No. of elements | Radiating element | Isolating structure | Edge to edge spacing (mm) | Isolation (dB) | Gain (dB) | Efficiency (%) | ECC       |
|------|-----------------|-------------------|---------------------|---------------------------|----------------|-----------|----------------|-----------|
| [2]  | 2               | Meander Line      | MTM                 | 5                         | 19             | 5.7       | 77.6           | Not specified |
| [3]  | 2               | Patch             | EBG                 | 15                        | 20             | Not specified | 85.9           | Not specified |
| [4]  | 2               | DRA               | MTM                 | 2.5                       | 46.5           | 7.90      | 91             | Not specified |
| [9]  | 2               | Patch             | EBG                 | 1                         | 20             | Not specified | 83             | Not specified |
| [18] | 2               | Patch             | Not given           | 5                         | 15             | 4.2       | 60             | .02        |
| NBCSRR| 2               | MTM               | MTM array           | 4                         | 47             | 8.15      | 84.14          | 0.015      |
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**Declarations**

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