Electromagnetic Soft Surface (EMSS) Integrated MIMO Antennas With Reduced Mutual Coupling And Cross-Polarization Radiation

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Abstract

For closely spaced microstrip antenna elements, Mutual Coupling (MC) is an inevitable phenomenon which degrades antenna performances like gain, radiation pattern, return loss, radiation efficiency etc. Lot of works have been done on the reduction of MC and published the results in the open literatures. This paper presents an approach to suppress MC between two closely spaced microstrip radiators. This is achieved by inserting properly designed EMSS structure between the radiating elements. This EMSS acts as an electrical wall between two rectangular patches and reduces mutual coupling up to 50 dB at resonance frequency of 4.35 GHz. In this attempt, Cross Polarization (XP) reduction of 12.5dB has also been achieved with a gain 5.40dBi for the proposed antenna. The centre to centre spacing between the antenna elements is taken as 22.1mm (0.32λ).The proposed MIMO antenna system can be used for satellite communication and radar system.

Introduction

In high performance aircraft, space craft, satellite communications, long distance radio telecommunications where the size, weight, cost etc are constraint the Microstrip Antennas (MSAs) are susceptible to these communications as MSAs are light weight, low cost, easy to install and flexible. However, it has certain disadvantages like narrow bandwidth, high MC, high orthogonal radiation etc [1].Researchers have proposed various techniques to overcome these disadvantages.

MIMO antenna systems have various advantages in the wireless applications because multiple antennas are used at both the transmitter and receiver ends. These multiple antennas are employed for transmitting/receiving good signal in a multipath fading scenario. MIMO antenna system increases data rate and reliability of communication without the need of extra power and bandwidth as compared to Single-Input-Single-Output (SISO) communication systems. Apart from these advantages, it has few disadvantages also, one of which is MC.

To design compact MIMO antenna, multiple antennas are placed on a single ground plane and MC takes place between adjacent antenna elements, as energy absorbed by one antenna when other is operating. As a result, electromagnetic interaction between the antenna elements will take place which is known as MC. MC occurred due to the signal interference and near field coupling between closely spaced two radiating elements. MC between two or more microstrip elements takes place due to separation, geometry and alignment of the antenna elements.

The voltage current relationship for coupled antenna system is written as, \( E = Z I \)
\[
\begin{pmatrix}
E_1 \\
E_2 \\
\vdots \\
E_m
\end{pmatrix}_{mx1} =
\begin{pmatrix}
Z_{11} & Z_{12} & Z_{13} & \ldots & Z_{1n} \\
Z_{21} & Z_{22} & Z_{23} & \ldots & Z_{2n} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
Z_{m1} & Z_{m2} & Z_{m3} & \ldots & Z_{mn}
\end{pmatrix}_{m \times n} 
\begin{pmatrix}
I_1 \\
I_2 \\
\vdots \\
I_n
\end{pmatrix}_{nx1}
\]

\(E_1, E_2, E_3, \ldots, E_m = \) Voltage applied to antennas 1, 2, \ldots, m.

\(I_1, I_2, I_3, \ldots, I_n = \) Current flowing in antennas 1, 2, \ldots, n.

\(Z_{11}, Z_{22}, Z_{mn} = \) Self impedances of antennas 1, 2, \ldots, n.

\(Z_{ij} \ (i \neq j) = \) Mutual impedance of antennas 1, 2, 3, \ldots, n.

Due to the effect of MC of multiple antennas \(Z_{ij} \ (i \neq j)\) are not the same. When, the Near Field Scatterer (NFS) is brought to the antenna 1, 2, 3, \ldots, n, the MC matrix changes. The presence of NFS, the above matrix changes to-

\[
\begin{pmatrix}
e_1 \\
e_2 \\
\vdots \\
e_n
\end{pmatrix} =
\begin{pmatrix}
Z_{11} + Z_{11}' & Z_{12} + Z_{12}' & \ldots & Z_{1n} + Z_{1n}' \\
Z_{21} + Z_{21}' & Z_{22} + Z_{22}' & \ldots & Z_{2n} + Z_{2n}' \\
\vdots & \vdots & \ddots & \vdots \\
Z_{m1} + Z_{m1}' & \ldots & \ldots & Z_{mn} + Z_{mn}'
\end{pmatrix} 
\begin{pmatrix}
i_1 \\
i_2 \\
\vdots \\
i_n
\end{pmatrix}
\]

\(e_1, e_2, \ldots, e_n = \) Change voltages.

\(i_1, i_2, \ldots, i_n = \) Change currents.

\(z_{mn} + z_{mn}' = \) Change impedances.

The above parameters are modified due to NFS and antenna spacing. Additional impedance parameter now added to the actual impedance effectively increases the total impedance of individual antenna elements. As a result, the efficiency as well as the gain of the antenna changes because of the changes in antenna current. As the impedance changes by MC the resonant frequencies as well as the gain of the antenna are also changed. In mobile communication if the spacing of the antenna elements are \(< \lambda/2\) the received signal will be affected by MC [2]. For patch antennas, dielectric constant of the substrate and also the thickness affect the MC. With higher dielectric constant and thickness, the MC is higher since more energy is coupled to the surface waves. To reduce the affect of MC, the isolation \((S_{21})\) between the antenna elements needs to be maximized. Authors in the open literatures have proposed various methods [3-33] to suppress the affect of MC.
In recent years, researchers have proposed various methods such as DGS[3-8], EBG[9-10], parasitic element[11-13], microstrip resonators[14-20], EMSS[21-24], FSS[25-27], metamaterial structure [28], coupling matrix based band stop filter[29], meander line [30-31] etc. to suppress the affect of MC between two patch antennas. DGS and EBGs are not very popular techniques as they cannot protect undesirable back radiation. It is seen in the open literatures that the parasitic elements, microstrip resonators, metamaterial structures, coupling matrix based band stop filter can reduce MC between closely spaced antenna elements.

Recently, a new technique known as Frequency Selective Surface (FSS) has been introduced to suppress MC between very closely spaced antenna elements. Design of FSS is very complicated and most of the cases FSS integrated antennas are erroneous after fabrication. Other than MC, there is one more drawback of probe feed antenna design for MIMO application. This drawback is the XP radiation as some degree of orthogonally polarized fields is always associated with the radiating energy [32-33]. Researchers suggest that the XP radiation level should be ≤ -20dB for better MIMO antenna performances.

Presently, researchers have introduced EMSS for reducing the affect of MC between the antenna elements. In our design, we have explored a new EMSS structure between two rectangular patch antennas as shown in Figure-3(b).This proposed EMSS created on the substrate between antenna elements effectively exhibits anti-resonance characteristics at the designed frequency and as a result both MC and XP are suppressed. It has been observed that the proposed EMSS structure does not affect the other characteristics of the antenna like return loss, bandwidth, antenna efficiency and radiation pattern in the principal plane.

**Design Methodology And Results**

For this design, we have taken FR4 substrate of dielectric constant 4.4, loss tangent 0.02 and thickness 1.6mm. The proposed antenna structure have been simulated using the method of moment (MOM) based IE3D electromagnetic simulator.

A single element rectangular patch antenna with a co-axial probe feed has been designed as shown in Figure-1(a). The length and width of the antenna is calculated from the standard formulae. The simulated S11 parameter of single element antenna is shown in Figure-1(b). The result shows that the single element antenna resonates at 4.35 GHz with a return loss of -27dB.

Figure-2 shows that the proposed MIMO antenna is constructed using two identical rectangular patches integrated with EMSS structure whose design parameters are given in the Table-1. Centre to centre distance between the antenna elements is taken as 22.1 mm (0.32 λ). The simulated S-parameter characteristics with and without EMSS structure is shown in Figure-3. From Figure-3, S21 of -17 dB without EMSS and -67dB with EMSS is observed. Here, the EMSS creates an indirect electromagnetic coupling path and acts as an anti-resonance mode with the resonance frequency of the excited patch and suppressed MC significantly.
The proposed EMSS structure with ports (Figure-4a) is simulated and S-parameter characteristics are shown in Figure-4(b).

It has been observed from the Figure-4(b) that isolation parameter (S_{21}) of this proposed EMSS structure is much less than -20dB at resonance which can be considered as good reduction of MC for antenna design. From this Figure, we find wide stop band (band gap) characteristics of EMSS structure at 4.35 GHz. The EMSS is basically acts as a band stop filter in this design. When one antenna is excited, the proposed EMSS structure rejects propagation of signals at resonance because of its stop band characteristic. Figure-5 exhibits the reduction of MC using vector current distributions of the antennas and the EMSS. In Figure-5(a), it has been observed that antenna-2 is affected by the MC when the antenna-1 is excited and Figure-5(a) & (b) shows effect of EMSS.

The MC is suppressed in the presence of the EMSS as this creates an oblique coupling path. This helps in getting a low MC between the antenna elements as shown in Figure-5(b). Same scenario is also observed in Figure-5(c) when antenna-2 is excited as this soft surface suppresses the surface current and near field coupling.

Figure-6 shows the simulated 3D radiation pattern. In this Figure, the gain of the proposed antenna is 5.40dBi. Figure-7 shows a graphical representation of co-polar and cross-polar radiation patterns of the single element antenna.

XP radiation degrades antenna radiation pattern in the principal plane. This undesirable radiation needs to minimize for achieving better radiation efficiency. From Figure-7, it has been observed that the difference of XP patterns is 12.5 dBi between without and with EMSS.

This proposed work has been compared with other similar works and a comparison table is given below.

Table-2. Comparison table of performance analysis with other similar works
| Reference                                      | Resonating Frequency (GHz) | Mutual Coupling (dB) |
|-----------------------------------------------|----------------------------|----------------------|
| [2] Inverted U-shaped microstrip resonators    | 5.25                       | 35                   |
| [3] Dumbel shaped DGS                         | 2.45                       | 30                   |
| [4] String of H-Shaped DGS                   | 2.4                        | 46                   |
| [5] Periodic DGS                              | 3.6                        | 10                   |
| [6] DGS                                       | 3.00                       | 20                   |
| [7] U-Shaped DGS and inverted U-shaped microstrip resonator | 2.45 | 20 |
| [8] Slotted ground plane                      | 5.8                        | 40                   |
| [9] 2D EBG structure                          | 7.45                       | 21                   |
| [10] UC-EBG Superstrate                       | 5.75                       | 10                   |
| [11] T-shaped parasitic element approach      | 5.8                        | 10                   |
| [12] Parasitic element                        | 4.3                        | 41                   |
| [13] two parasitic microstrips                | 2.4                        | 18.6                 |
| [14] Matrix of C-Shaped resonators            | 6.3                        | 18                   |
| [15] Split ring resonator                     | 5.0                        | 10                   |
| [16] I-shaped resonator                       | 4.36                       | 34                   |
| [17] Dumbell-Shaped Resonator (DSR)           | 5.2                        | 12                   |
| [18] Dollar shaped electrical resonator        | 5.74                       | 43                   |
| [19] Microstrip I-section                     | 3.95                       | 30                   |
| [20] Microstrip resonator                     | 5.9                        | 19.5                 |
| [21] Electromagnetic soft surface             | 3.65                       | 35                   |
| [22] Miniaturized soft surface structure       | 5.8                        | 10                   |
| [23] High impedance electromagnetic surfaces  | 3.8                        | 20.7                 |
| [24] Soft surface                             | 1.75                       | 6                    |
| [25] FSS                                      | 30.5                       | 10                   |
| [26] Planar frequency-selective surface structure | 6.4  | 14 |
| [27] Modified serpentine structure (MSS)      | 2.45                       | 34                   |
Antenna Fabrication And Measurement

A finite ground plane with FR4 substrate of dimension (41.05 × 24.55) mm$^2$ has been taken for proposed two-element MIMO antenna design. The dimension of EMSS is considered as (6.7 × 20.725) mm$^2$. This antenna structures are fabricated on FR4 substrate whose loss tangent and thickness are 0.2 and 1.6 mm respectively. To validate the concept of MC reduction, both antennas (with and without EMSS) have been fabricated and measured. The fabricated antennas are shown in the Figure-8 and Figure-9. The measured results, shown in Figure-10, have been compared with the simulated ones.

From Figure-10, we observed that there is a little mismatch between simulated and measured results. These discrepancies may occur due to fabrication and measurement errors. Figure-11 shows the measured results of co-polar and XP radiations, and the same are compared with the simulated ones.

The above Figures shows that the measured co-polar and XP radiation patterns are almost tallyed with the simulated results.

Conclusion

The proposed MIMO structure integrated with EMSS has been successfully designed with very low MC and XP at resonance frequency of 4.35 GHz. In the design, the EMSS structure is mounted onto the antenna substrate in between the radiating patches to suppress the surface wave and as a result huge reduction of MC (50dB) has been achieved. Furthermore, EMSS causing 12.5dB suppression in XP radiation without distorting other parameter like return loss, bandwidth, efficiency, gain, co-polar radiation.

Table-3. Comparison table for XP radiation with different reported works

| Ref | Proposed Technique             | XP radiation Reduction (dB) | Remarks                   |
|-----|--------------------------------|----------------------------|----------------------------|
| [4] | String of H-Shaped DGS        | 11.0                       | DGS offer high back radiation |
| [17] | dumbbell-shaped resonator      | 7.5                        | No back radiation          |
| [33] | spiral-ring resonator          | 7.0                        | No back radiation          |
| -   | Proposed EMSS                 | 12.5                       | No back radiation          |
etc. The proposed MIMO antenna integrated with EMSS achieved a gain of 5.40 dBi at resonance. This proposed antenna is suitable for C-band applications like satellite and radar communication.

**Declarations**

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**DISCLOSURE STATEMENT**

No potential conflict of interest was reported by the authors.

**DATA TRANSPARENCY**

Not applicable

**CODE AVAILABILITY**

Not applicable

**AUTHORS’ CONTRIBUTIONS**

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Swati Bhattacharjee], [Santimoy Mandal] and [Chandan Kumar Ghosh]. The first draft of the manuscript was written by [Swati Bhattacharjee] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Figures

Figure 1

(a) Schematic of the unit element antenna with dimension (mm) and (b) S11 parameter
Figure 2

(a) Schematic diagram of patch antennas having EMSS structure  
(b) The EMSS structure
Figure 3

Simulated S-parameter variation with frequency in presence and absence of the EMSS structure

Figure 4
(a) EMSS with port (b) simulated electrical characteristics of the EMSS structure (c) simulated vector current distribution of the EMSS when patch is excited

Figure 5

Simulated vector current distribution (a) without EMSS, (b) with EMSS when antenna-1 excited (c) with EMSS when antenna-2 excited
Figure 6

3D Radiation pattern of the single element of MIMO antenna
Figure 7

Co-polar & XP radiation patterns (a) without EMSS (b) with EMSS

Figure 8

Front view of fabricated antennas (a) without EMSS (b) with EMSS
Figure 9

Back view of fabricated antennas (a) without EMSS (b) with EMSS

Figure 10

Measured and simulated S-parameters results
Figure 11

Measured and simulated co-polar/ XP radiation of the proposed MIMO antenna. The above figures show that the measured co-polar and XP radiation patterns are almost tallied with the simulated results.