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

Swati Bhattacharjee
Asansol Engineering College
Santimoy Mandal
RVS College of Engineering and Technology
Chandan Kumar Ghosh (mcet_ckg@yahoo.com)
Dr. B.C.Roy Engineering College

Research Article

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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=ZI

$$
\begin{pmatrix} E_1 \\ E_2 \\ \cdot \\ \cdot \\ \cdot \\ E_m \end{pmatrix}_{m \times 1} = \begin{pmatrix} Z_{11} & Z_{12} & Z_{13} & \ldots\ldots\ldots & Z_{1n} \\ Z_{21} & Z_{22} & Z_{23} & \ldots\ldots\ldots & Z_{2n} \\ \cdot & & & \cdot & \\ \cdot & & & \cdot & \\ \cdot & & & \cdot & \\ Z_{m1} & Z_{m2} & Z_{m3} & \ldots\ldots\ldots & Z_{mn} \end{pmatrix}_{m \times n} \begin{pmatrix} I_1 \\ I_2 \\ \cdot \\ \cdot \\ \cdot \\ I_n \end{pmatrix}_{n \times 1}
$$

E_1, E_2, E_3… Em = Voltage applied to antennas 1, 2 …m.

I_1, I_2, I_3…I_m = Current flowing in antennas 1, 2…n.

Z_{11}, Z_{22}…Z_{mn}= Self impedances of antennas 1, 2…n.

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

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

$$
\begin{pmatrix} e_1 \\ e_2 \\ \cdot \\ e_n \end{pmatrix} = \begin{pmatrix} z_{11}+z_{11}' & z_{12}+z_{12}' \ldots\ldots & z_{1n}+z_{1n}' \\ z_{21}+z_{21}' & z_{2n}+z_{2n}' \ldots\ldots & z_{2n}+z_{2n}' \\ \cdot & & \cdot \\ z_{m1}+z_{m1}' & \ldots\ldots\ldots\ldots & z_{mn}+z_{mn}' \end{pmatrix} \begin{pmatrix} i_1 \\ i_2 \\ \cdot \\ i_n \end{pmatrix}
$$

e_1, e_2…e_n= Change voltages.

i_1, i_2…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 $\leq$ -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]Dumbbell-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

[28] Modified split ring resonator metamaterial structure	5.3	23
[29] Coupling matrix based band stop filter	3.0	28
[30] meander line	5.2	40
[31]Meander line resonator	2.8	8
Proposed design	**4.38**	**50**

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**

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 tallied 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 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.

References

1. Balanis C. Antenna theory: analysis and design. Hoboken (NJ): Wiley Interscience; 2005.
2. Chandan Kumar Ghosh, "A compact 4-channel microstrip MIMO antenna with reduced mutual coupling" 2016 International Journal of Electronics and Communications (AEÜ), Vol.70, pp-873-879, 2016.
3. Lin Teng, Jingrui Pei and Shoulin Yin "Mutual Coupling Optimization of Compact Microstrip Array Antenna" Indonesian Journal of Electrical Engineering and Computer Science Vol. 4, No. 3, pp. 538-541, December 2016.
4. Juin Acharjee , Kaushik Mandal , and Sujit Kumar Mandal, "Reduction of Mutual Coupling and Cross Polarization of a MIMO/Diversity Antenna using a String of H-Shaped DGS" AEU-International Journal of Electronics and Communications. doi:10.1016/j.aeue.2018.09.037.

5. Kun Wei , Jian-Ying Li , Ling Wang , Zi-Jian Xing , Rui Xu, “Mutual Coupling Reduction of Microstrip Antenna Array by Periodic Defected Ground Structures” 2016 IEEE 5th Asia-Pacific Conference on Antennas and Propagation (APCAP). doi:10.1109/apcap.2016.7843257.
6. Zhaolin Zhang , Kun Wei , Jian Xie , Jianying Li , Ling Wang, “The MIMO Antenna Array with Mutual Coupling Reduction and Cross-polarization Suppression by Defected Ground Structures” Radio engineering, Vol. 27, No. 4, December 2018, DOI: 10.13164/re.2018.0969.
7. Chandan K. Ghosh, BappadityaMandal, and Susanta K. Parui “Mutual coupling reduction of a dual-frequency microstrip antenna array by using U-shaped DGS and inverted U- shaped microstrip resonator” Progress in Electromagnetic Research C, Vol. 48, 61–68
8. J. OuYang, F. Yang, and Z. M. Wang, “Reducing Mutual Coupling of Closely Spaced Microstrip MIMO Antennas for WLAN Application” IEEE Antennas and Wireless Propagation Letters, Vol. 10, 2011.
9. Hassan Sajjad, Sana Khan, and Ercument Arvas “Mutual Coupling Reduction in Array Elements Using EBG Structures” International Applied Computational Electromagnetics Society Symposium - Italy (ACES-2017). doi:10.23919/ropaces.2017.7916410.
10. Hossein Sarbandi Farahani, Mehdi Veysi, Manouchehr Kamyab, and Alireza Tadjalli, “Mutual Coupling Reduction in Patch Antenna Arrays Using a UC-EBG Superstrate” IEEE Antennas and Wireless Propagation Letters, Vol. 9, 2010.
11. Faizan Faraz, Qinlong Li, Xiaoming Chen, Muhammad Abdullah, Shuai Zhang, Anxue Zhang “Mutual Coupling Reduction for Linearly Arranged MIMO Antenna” Cross Strait Quad-Regional Radio Science and Wireless Technology Conference (CSQRWC-2019). doi:10.1109/csqrwc.2019.8799266.
12. Emadeddin, A., Shad, S., Rahimian, Z., & Hassani, H. R. “High mutual coupling reduction between microstrip patch antennas using novel structure”. AEU - International Journal of Electronics and Communications (2017)., 71, 152–156. doi:10.1016/j.aeue.2016.10.017.
13. Xu-bao Sun , Mao-yong Cao, “Mutual coupling reduction in an antenna array by using two parasitic microstrips” AEU - International Journal of Electronics and Communications, 74, 1–4. doi:10.1016/j.aeue.2017.01.013.
14. Raghad Ghalib, Saadallah Alsultan and Gölge Ögücü, Yetkin “Mutual Coupling Reduction of E-Shaped MIMO Antenna with Matrix of C-Shaped Resonators Hindawi International Journal of Antennas and Propagation Volume 2018, Article ID 4814176, DOI-10.1155/2018/4814176.
15. Bait-Suwailam, M. M., Siddiqui, O. F., &Ramahi, O. M. “Mutual Coupling Reduction between Microstrip Patch Antennas Using Slotted-Complementary Split-Ring Resonators”. IEEE Antennas and Wireless Propagation Letters, 9, 876–878. 2010.
16. Swati Bhattacharjee, Chandan Kumar Ghosh “Reduction of Mutual Coupling between two adjacent Microstrip antennas using I-shaped Resonators” IEEE International conference on advent trends in Multidisciplinary Research and Innovation (ICATMRI-2020).

17. Chandan Kumar Ghosh, R. Hazra, A. Biswas, A.K. Bhattachrjee, and S.K. Parui , “Suppression of crosspolarization and mutual coupling between dual trace dual column coaxial microstrip array using dumbbell-shaped resonator” Microwave and Optical Technology Letters / Vol. 56, No. 9,PP.2182-2186,September 2014, DOI 10.1002/mop.28531.
18. Santimoy Mandal and Chandan Kumar Ghosh, “Reduction of the Mutual Coupling in Patch Antenna Arrays Based on Dollar Shaped Electrical Resonator” Lecture notes on Electrical Engineering 602, proceeding of 2nd international conference on Communication, Devices and Computing ICCDC 2019, Springer, p.p-71-76.
19. Chandan Kumar Ghosh and Susanta Kumar Parui “Reduction of mutual coupling between E-shaped microstrip antennas by using a simple microstrip I-section” Microwave and Optical Technology Letters Vol. 55, No. 11, 2013.
20. Chandan Kumar Ghosh ,ManishPratap, Rahul Kumar, Saurabh Pratap “Mutual Coupling Reduction of Microstrip MIMO Antenna Using Microstrip Resonator “Wireless Personal Communications,2020, DOI 10.1007/s11277-020-07138-z.
21. Chandan Kumar Ghosh and Sourav Moitra“Study of decoupling between patch elements of microstrip array using electromagnetic soft surface” Journal of Electromagnetic waves and applications,Vol.32,Issue-9,PP-1126-1135, 17 Jan 2018.
22. S. Abushamleh, H. Al-Rizzo, A. Abbosh,Ahmed A. Kishk “Mutual coupling reduction between two patch antennas using a new miniaturized soft surface structure”. IEEE AP-S Dig. 2013. p. 1822–1823.
23. Mohammad Tariqul Islam and Md. Shahidul Alam, “Design of High Impedance Electromagnetic Surfaces for Mutual Coupling Reduction in Patch Antenna Array” Materials 2013, 6, 143-155; doi:10.3390/ma6010143.
24. Óscar Quevedo-Teruel, Luis Inclán-Sánchez, and Eva Rajo-Iglesias, “Soft Surfaces for Reducing Mutual Coupling Between Loaded PIFA Antennas” IEEE Antennas and Wireless Propagation Letters, 9, 91–94. doi:10.1109/lawp.2010.2043632.
25. M. Akbari, M.M. Ali, M. Farahani, A.R. Sebak and T. Denidni, “Spatially mutual coupling reduction between CP-MIMO antennas using FSS superstrate” ELECTRONICS LETTERS 13th April 2017 Vol. 53 No. 8 pp. 516–518.
26. Ehsan Beiranvand, Majid Afsahy and Vahid Sharbati, “Reduction of the mutual coupling in patch antenna arrays based on EBG by using a planar frequency-selective surface structure” International Journal of Microwave and Wireless Technologies, doi:10.1017/S1759078715001440.
27. Arun, H., Sarma, A. K., Kanagasabai, M., Velan, S., Raviteja, C., & Alsath, M. G. N. “Deployment of Modified Serpentine Structure for Mutual Coupling Reduction in MIMO Antennas”. IEEE Antennas and Wireless Propagation Letters (2014)., 13, 277–280. doi:10.1109/lawp.2014.2304541.
28. Kai Yu, Xiaoguang Leo Liu,Yingsong Li “Mutual Coupling Reduction of Microstrip Patch Antenna Array Using Modified Split Ring Resonator Metamaterial Structures” IEEE International Symposium

on Antennas and Propagation & USNC/URSI National Radio Science Meeting-2017 doi:10.1109/apusncursinrsm.2017.8073186.

29. Bilal Tütüncü, “Mutual Coupling Reduction Using Coupling Matrix Based Band Stop Filter” International Journal of Electronics and Communications doi: 10.1016/j.aeue. 153342.
30. Qian Li, Chong Ding, Xia Lei, Gangxiong Wu, Ruichao Yang, Minzhi Huang, Yubin Gong, Zhigang Lu, Zhanliang Wang, Hairong Yin, Yanyu Wei, “Mutual Coupling Reduction in Patch Antenna Arrays” 2018 IEEE International Vacuum Electronics Conference (IVEC). doi:10.1109/ivec.2018.8391624.
31. Jeet Ghosh, Sandip Ghosal , Debasis Mitra, and Sekhar Ranjan Bhadra Chaudhuri “Mutual Coupling Reduction between Closely Placed Microstrip Patch Antenna Using Meander Line Resonator” 2016 Progress In Electromagnetics Research Letters, Vol. 59, 115–122.
32. J.R. James and P.S. Hall, Handbook of microstrip and printed antennas, Wiley, New York, 1997.
33. Chandan Kumar Ghosh, Biswarup Rana and Susanta Kumar Parui, “Reduction of cross polarization of slotted microstrip antenna array using spiral-ring resonator” Microwave and Optical Technology Letters, Vol. 55, No. 9, September 2013, DOI 10.1002/mop27778.

Figures

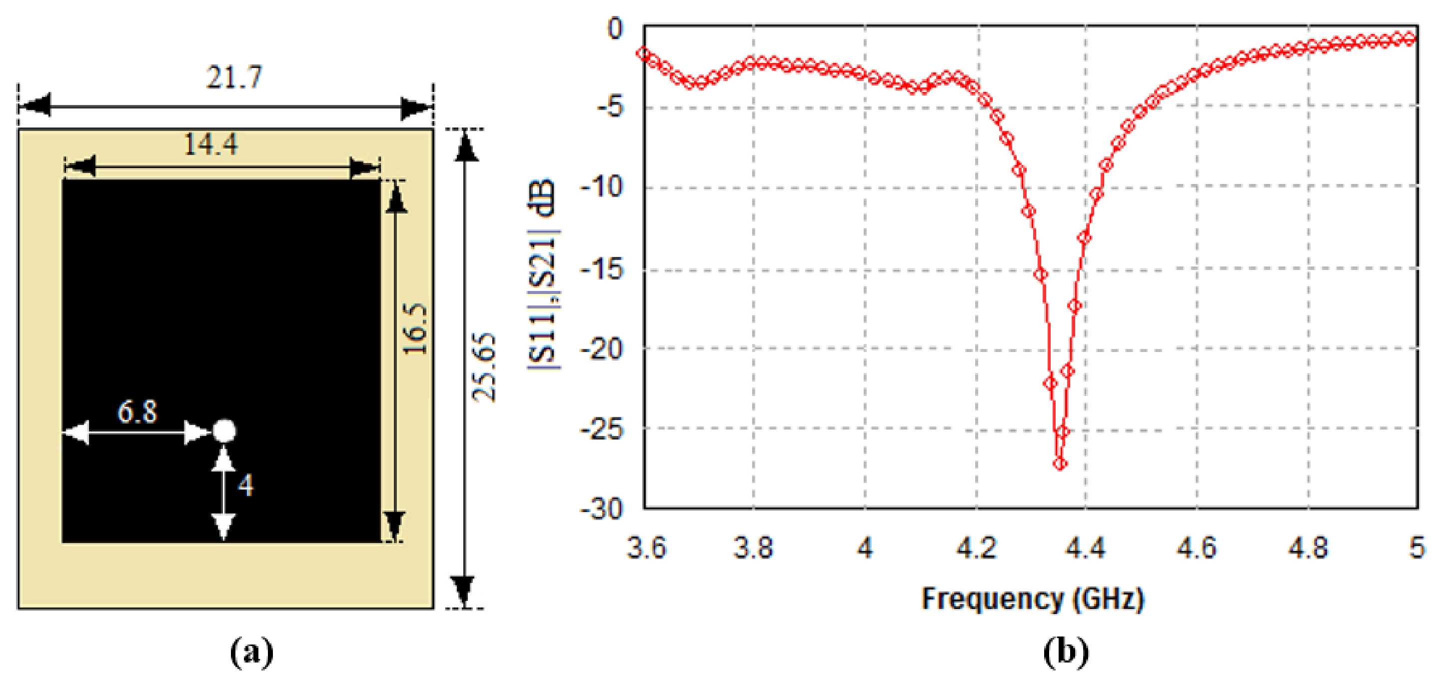


Figure 1

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

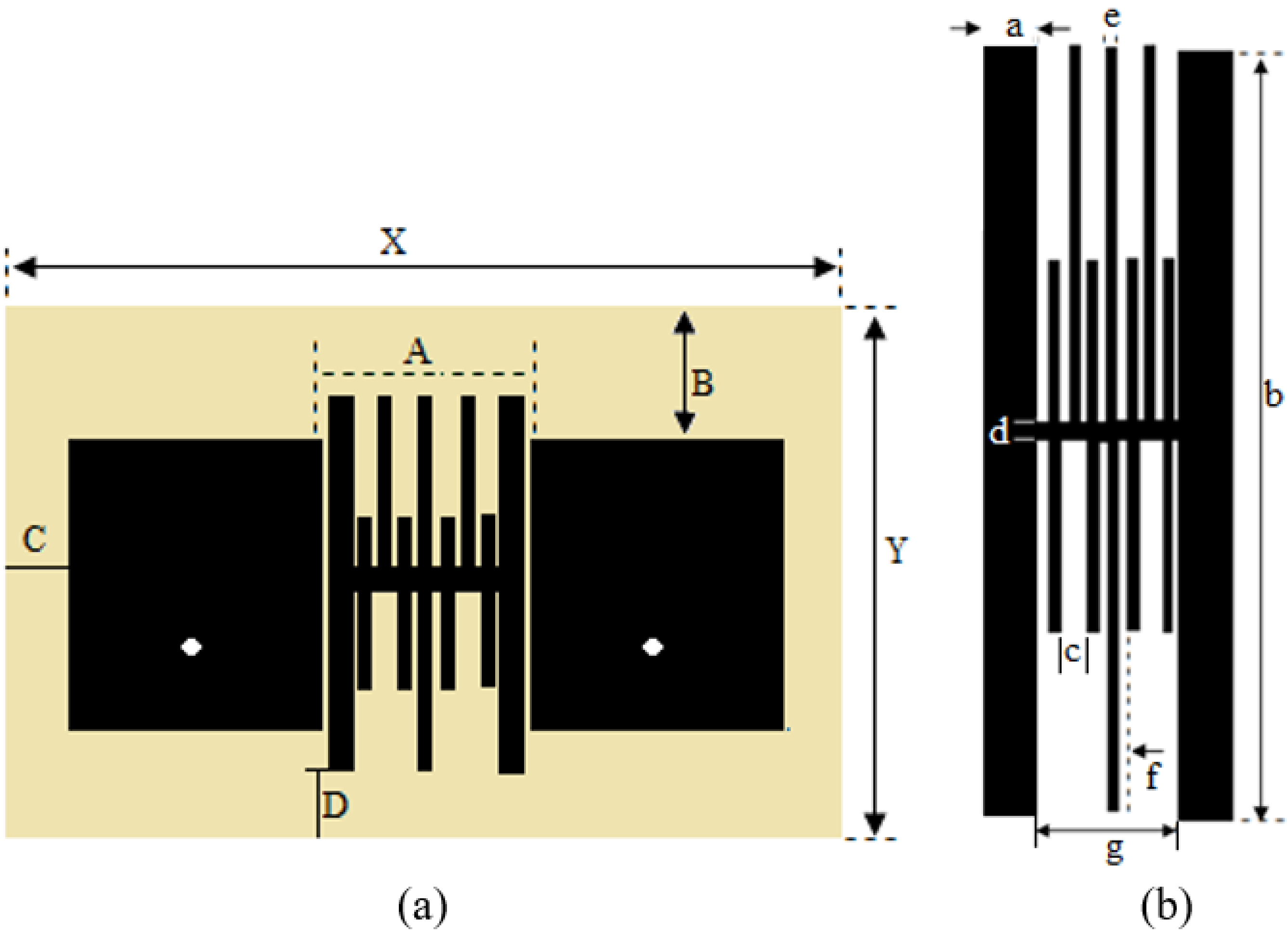


Figure 2

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

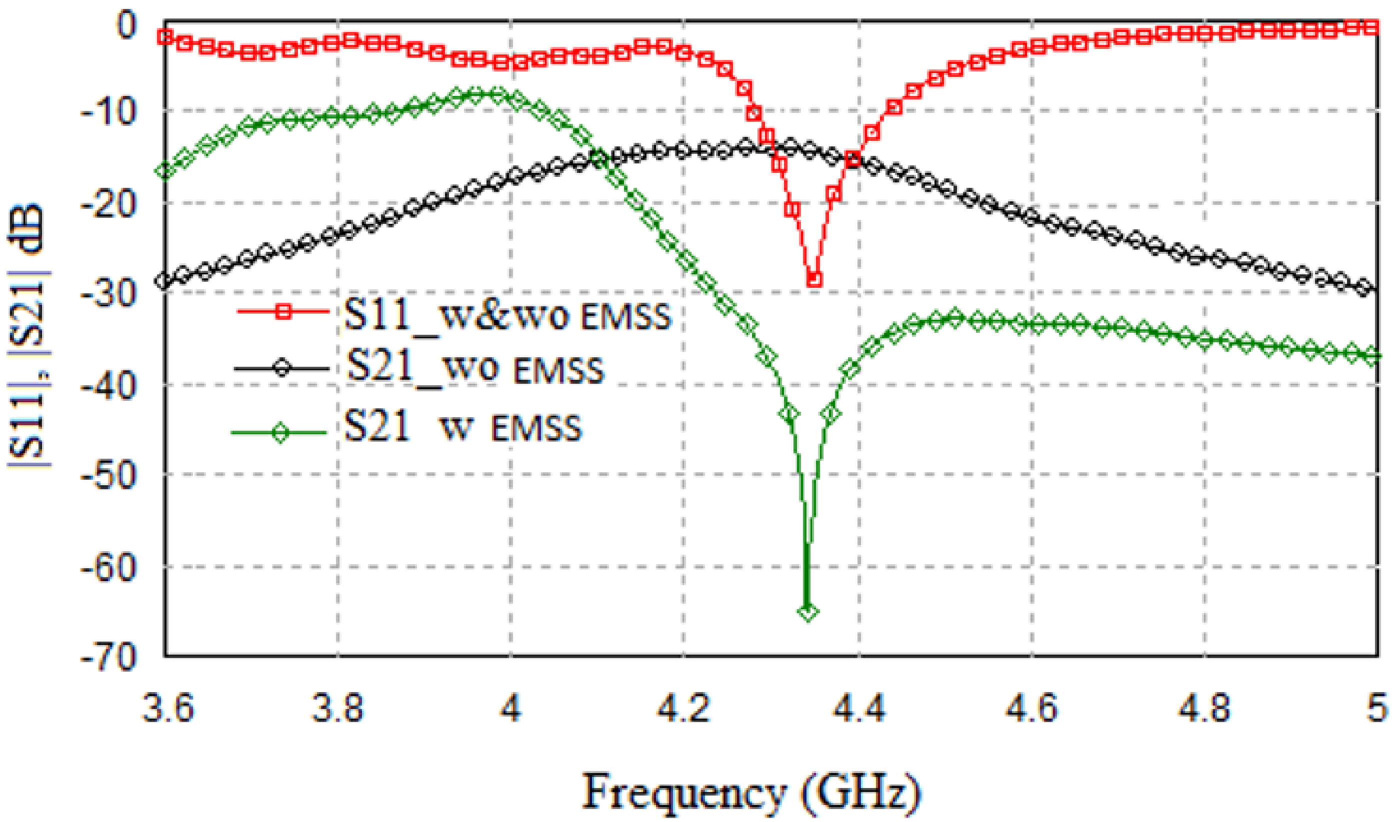


Figure 3

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

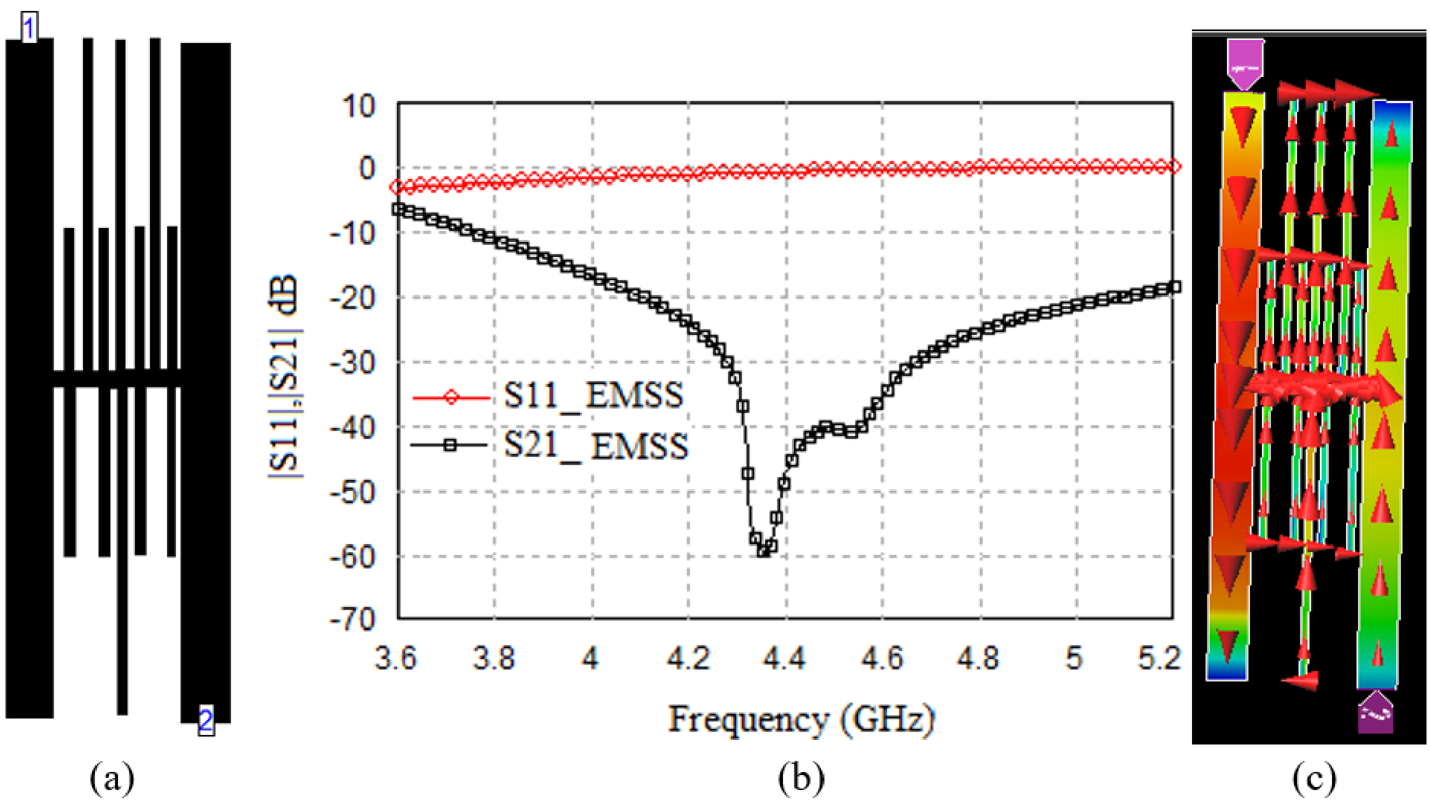


Figure 4

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

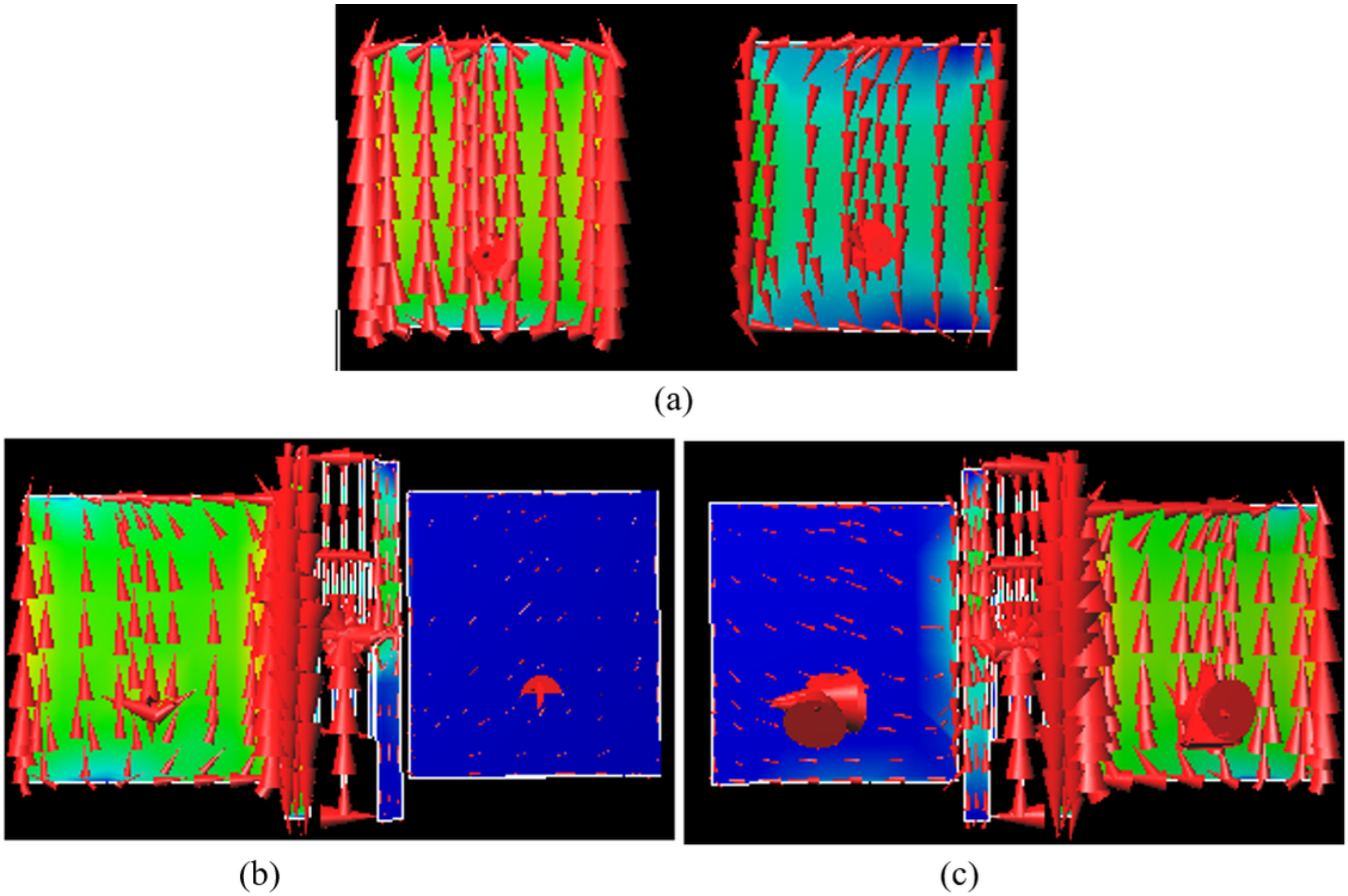


Figure 5

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

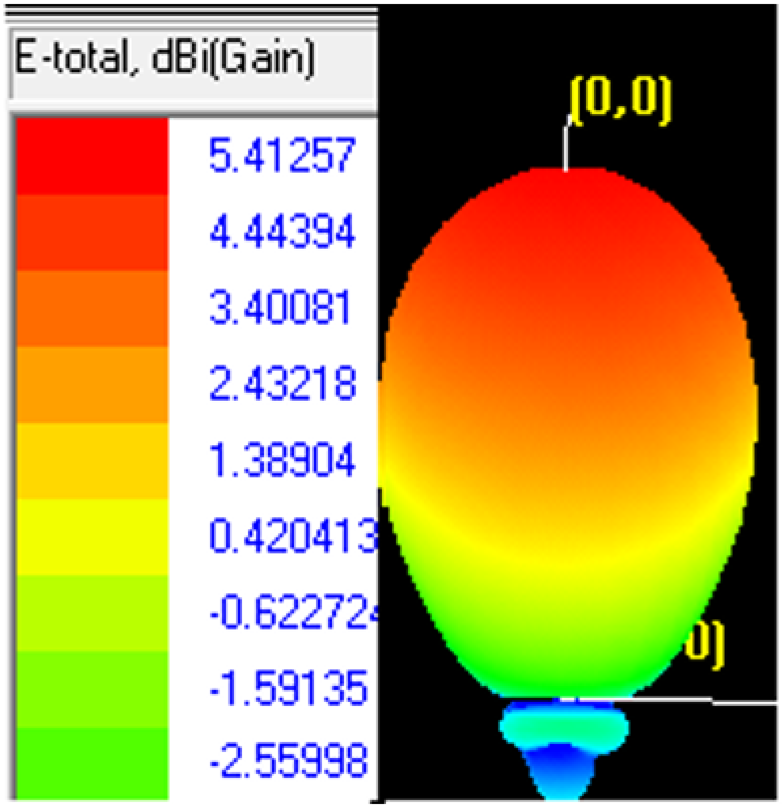
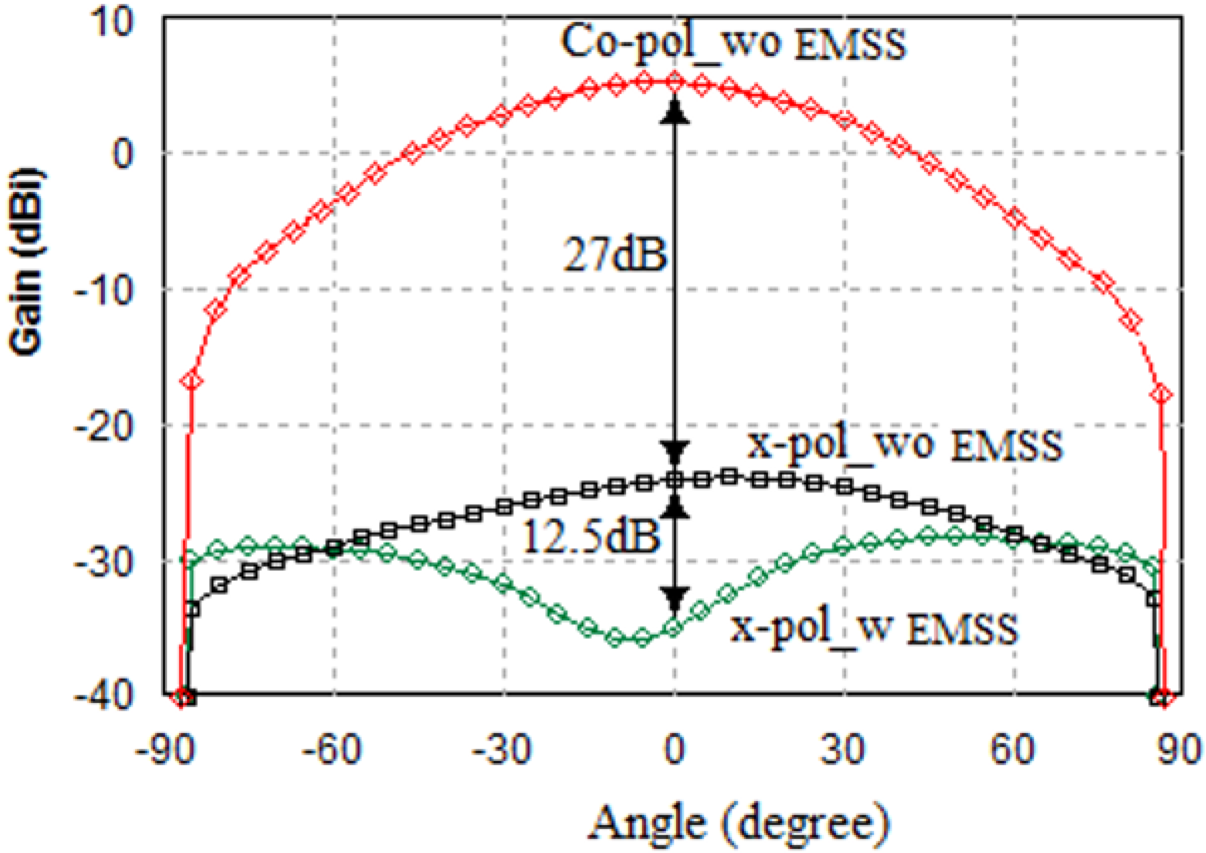


Figure 6

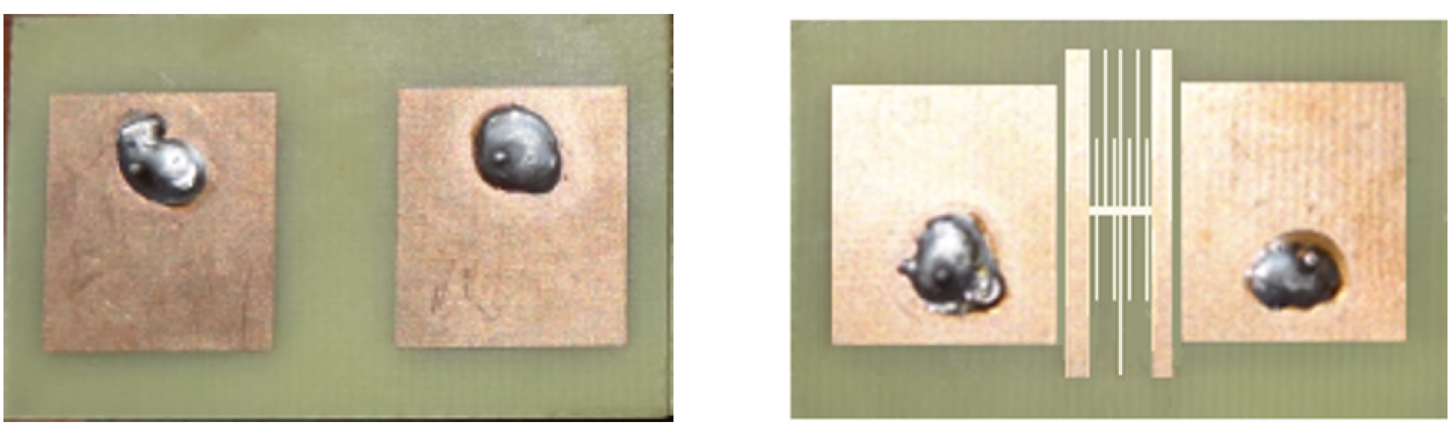
3D Radiation pattern of the single element of MIMO antenna



(b)

Figure 7

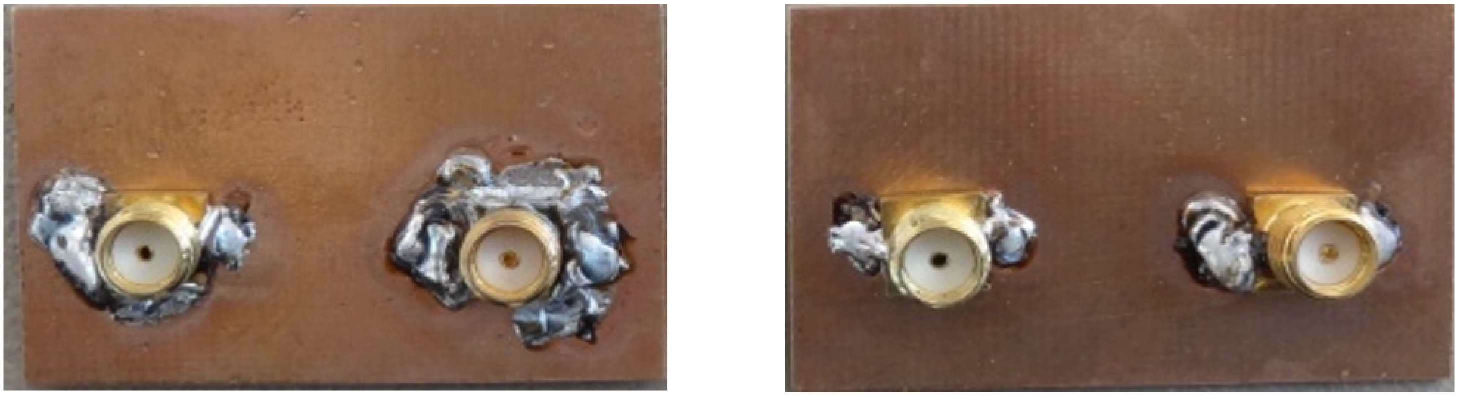
Co-polar & XP radiation patterns (a) without EMSS (b) with EMSS



(a) (b)

Figure 8

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



(a) (b)

Figure 9

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

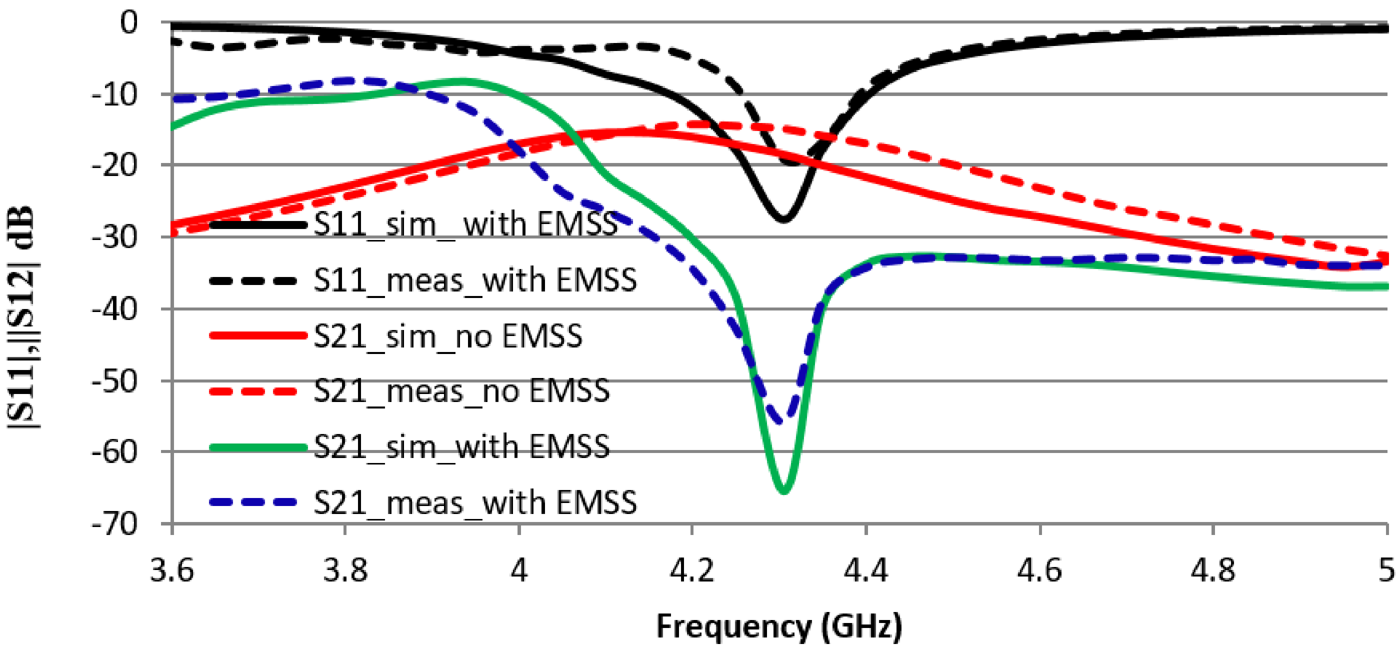


Figure 10

Measured and simulated S-parameters results

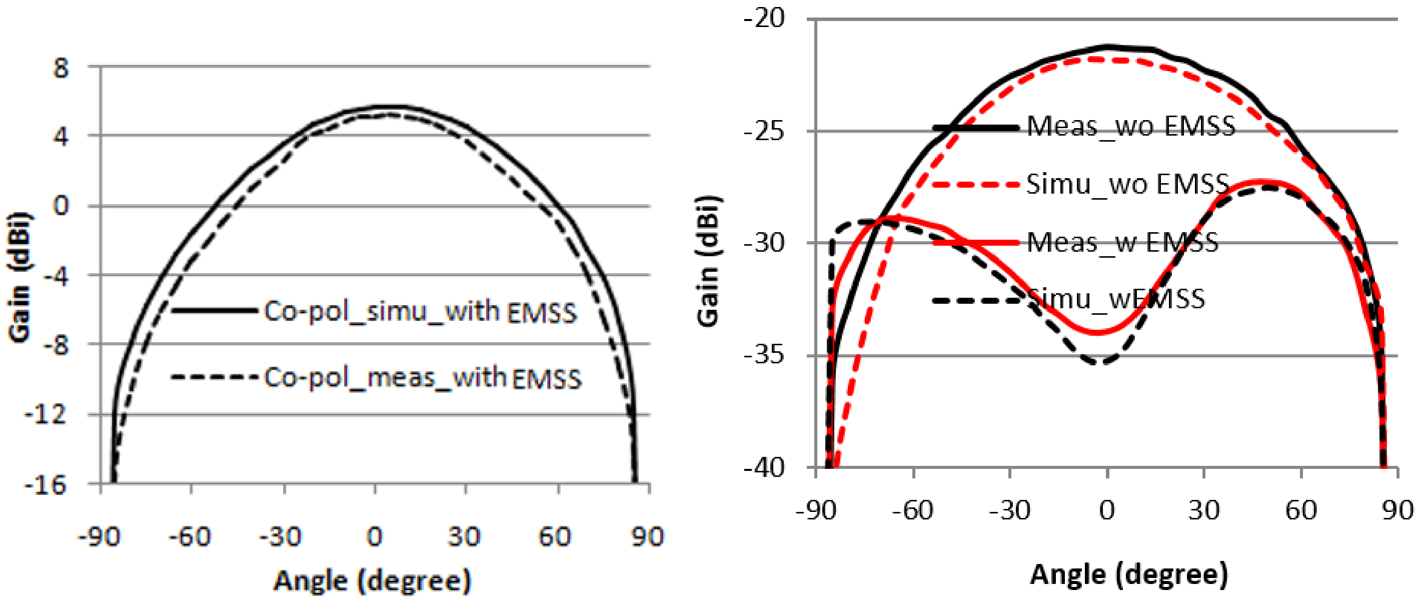


Figure 11

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