Mutual Coupling Reduction of a MIMO Antenna Array Using 3-D Novel Meta-material Structures

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Abstract **─** A 3-D metamaterial structure (3DMMS) is proposed and is used to reduce mutual coupling of a two-element patch antenna array. The 3DMMS consists of an upper M-shaped patch and two lower U-shaped patches, which are connected by two shorted pins. The proposed 3DMMS has a negative permeability at 2.35-2.45 GHz band, which covers the operation band of the patch antenna array with an edge-to-edge array-element distance of $0.13\lambda_0$. Five designed 3DMMS cells are embedded into the substrate between two antenna elements, which has a 0.1mm vertical distance to the patch antennas. The proposed antenna is optimized, fabricated and measured. The results show that about 18 dB mutual coupling reduction is achieved by using the 3DMMS without affecting the operating bandwidth and radiation characteristics.

Index Terms **─** Metamaterial structure, microstrip patch antenna array, mutual coupling reduction.

I. INTRODUCTION

Recently, planar antennas have been extensively studied and integrated into various portable and compact mobile terminals [1, 2]. To improve the spectrum efficiency of a wireless communication system, one of the effective methods is to use the multiple-input multiple output (MIMO) technology [3-4]. As a MIMO system, multiple antennas are used for both the transmitters and receivers to improve the channel capacities. Thus, small and broadband MIMO antennas are required to construct desired high-capacity next-generation mobile communication systems.

Moreover, smaller and higher data transmission devices are needed to install a MIMO antenna in a limited space. As a result, the distance between the antenna elements are becoming narrower, which will not only result in a strong mutual coupling between the array elements but also increase the spatial correlation. Additionally, the mutual coupling between antenna elements is an urgent problem, because the inter-coupling will affect wireless system performance, antenna efficiency, as well as amplitude and phase errors [5-19].

In order to reduce the mutual coupling of planar antenna array, various decoupling methods have been presented. Defected ground structure (DGS) is proved to be an effective method to reduce the mutual coupling and enhance the isolation, which is etched various slots in the common ground plane. Then, an S-shaped periodic DGS is utilized to obtain more than 40 dB mutual coupling reduction between antenna elements. After that, a novel fractal DGS (FDGS) is designed to enhance the isolation of a dual elements antenna array [6-7]. Then, the stub technologies have been investigated to reduce the mutual coupling in MIMO array [8-11]. Moreover, electromagnetic band gap (EBG) structure has been utilized to reduce the mutual coupling in a two-element antenna array [12-15]. Then, several EBG structures have been reported to improve the isolation between the antenna elements [12-15]. However, some of the EBG structures are complex and others have high profile, which is difficult in the practical terminal applications. Furthermore, many other solutions have been presented to reduce the strong mutual coupling, including conducting wall [16], neutralization line [17], parasitic structures and meta-material based decoupling structures [18-19]. However, the mutual coupling is reduced only 6 dB by the wave-guided meta-material given in [19].

In this paper, a 3-D meta-material structure developed and integrated into a two-element MIMO antenna array to reduce the mutual coupling. The designed meta-material unit is comprised of an upper M-shaped patch

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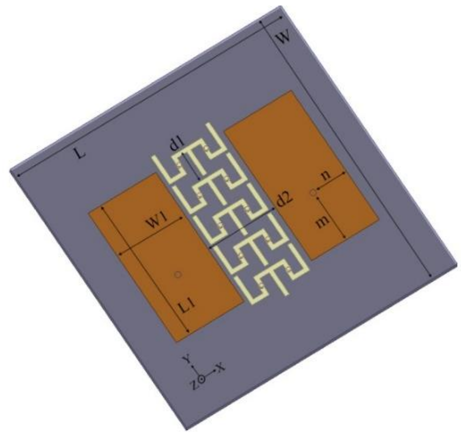
and two lower U-shaped patches, and which are connected by two shorted pins. Then, five 3-D meta-material cells are embedded into the substrate into the substrate between two antenna elements, which has a vertical distance of 0.1mm from 3-D meta-material cells to the top surface of the substrate. By using the proposed meta-material structures, more than 18 dB mutual coupling reduction is achieved, which greatly enhances the isolation without affecting the operating bandwidth and radiation characteristics. The proposed structure is embedding in the FR4 substrate, which effectively reduce the profile of the MIMO array and give small effects on the bandwidth and the radiation patterns. Also, the proposed structure provides better isolation.

II. METAMATERIAL UNIT AND ANTENNA CONFIGURATION

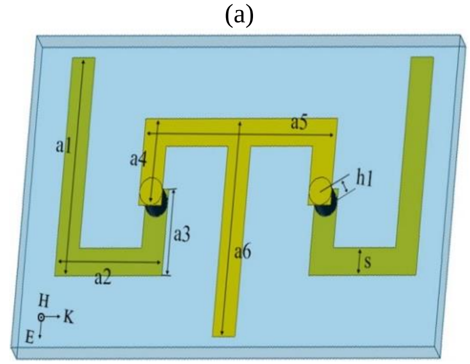
The configuration of the proposed two-element MIMO antenna array with developed 3-D meta-material structure is depicted in Fig. 1, which is fabricated on a FR-4 substrate with a relative permittivity of 4.4, a loss tangent of 0.02, and a thickness of 1.6mm. The total size of the MIMO antenna is 60 × 60mm^2. Two rectangle patch antennas with 50-Ohm coaxial feeding are utilized to construct the two-element MIMO antenna array whose edge-to-edge antenna element distance is 0.13λ_0. To reduce the mutual coupling, a 3-D meta-material is developed and incorporated into the MIMO antenna. It is found that the MIMO antenna consists of two identical rectangle patch antennas fed by coaxial lines, five 3-D meta-material cells are embedded in the FR-4 substrate to improve the isolation of the MIMO antenna. The vertical distance from the upper M-shaped patch of the designed 3-D meta-material to the top surface of the FR-4 substrate is very small. The 3-D meta-material cell is shown in Fig. 1 (b). It is noted that the proposed meta-material is a non-planar structure, which is composed of an upper M-shaped patch and two lower U-shaped patches. Both of the upper and lower patches are connected via two shorted pins, which is a 3-D meta-material structure. The proposed MIMO antenna and the 3-D meta-material are optimized by using the HFSS and the optimal parameters are: W=60, L=60, W1=15, L1=30, d1=7, d2=15, m=11, n=7.5, s=0.8, a1=6.3, a2=3, a3=2.5, a4=2.5, a5=5.2, a6=6.3, h=1.6, h1=0.8, h2=0.1, (unit:mm).

III. PERFORMANCE OF THE PROPOSED 3-D META-MATERIAL AND THE MIMO ANTENNA

In order to master the electromagnetic properties of proposed 3-D meta-material cell, S-parameters retrieval method is utilized to retrieve the electromagnetic parameters of the cell. The reflection coefficient (S_{11}) and transmission coefficient (S_{12}) are obtained by the HFSS, which are shown in Fig. 2 (In order to write well, S_{11} and S_{12} are also denoted as S11 and S12, respectively). It is observed that a band-gap characteristic appears around 2.4 GHz, where the electromagnetic waves are almost reflected. Moreover, the retrieved permeability of developed 3-D meta-material cell is given in Fig. 2. We can see that the real of permeability of the 3-D meta-material cell is negative from 2.35 GHz to 2.45 GHz, which can be used to block the surface wave propagation.



(a)



(b)

Fig. 1. Geometry structure of the proposed MIMO antenna: (a) MIMO antenna and (b) meta-material cell.

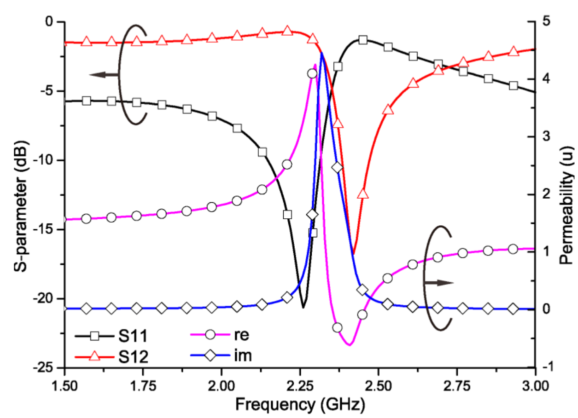


Fig. 2. Characteristics of the proposed 3-D meta-material cell.

Then, five proposed 3-D meta-material cells are integrated into the designed two-element MIMO antenna. The performance of the MIMO antenna with and without the proposed 3-D meta-material is investigated by using the HFSS, and the simulation results are compared in Fig. 3. It can be seen that the proposed MIMO antenna provide about 100MHz bandwidth. The resonance frequency of the MIMO antenna is almost same. However, the mutual coupling of the MIMO antenna with the proposed 3-D meta-material cells drops more than 18 dB in comparison with the MIMO antenna without the meta-material structure. That is to say that the proposed MIMO antenna with proposed 3-D meta-material cells provides a significant improvement with respect to the isolation.

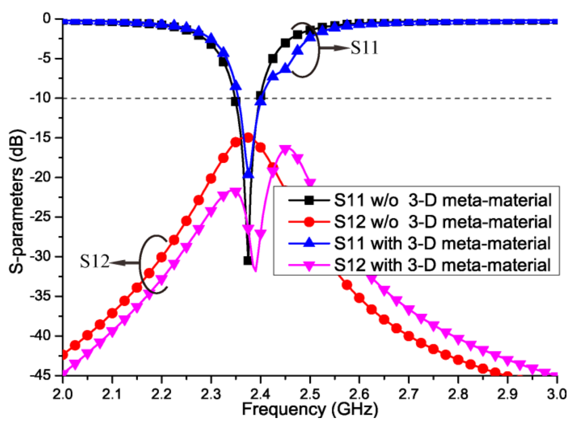


Fig. 3. Impedance bandwidth and mutual coupling of the MIMO antenna.

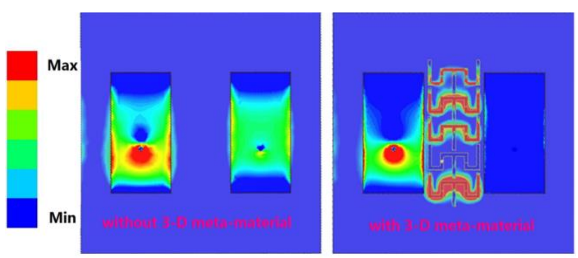


Fig. 4. Current distribution of the proposed MIMO antenna array at 2.38 GHz.

To further understand the effects of proposed 3-D meta-material cells in the MIMO antenna, the current distributions on the MIMO antenna are investigated and shown in Fig. 4 at the 2.38 GHz operation band. Obviously, without the proposed 3-D meta-material structure, strong currents are coupled from one antenna to another patch antenna, whereas only weak surface currents are induced on another patch when the proposed 3-D meta-material structure is loaded. In this case, a large current appears on the proposed 3-D meta- material structure, which blocks the surface current and reduces the mutual coupling of the closed assignment MIMO antenna array.

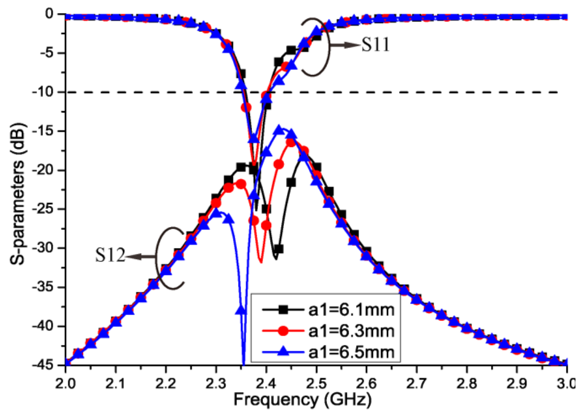
Next, the key parameter effects on the impedance bandwidth and isolation of the MIMO antenna with respect to S11 and S21 are presented by considering a1, a3, h1 and h2. Figure 5 (a) gives the effects of a1 on the S-parameter of the MIMO antenna. It is found that the operating band of the MIMO antenna is almost constant, while the isolation is improved in terms of S12.

Moreover, the S12 moves from high frequency to low frequency when a1 ranges from 6.1mm to 6.5mm. Parameter a3 has an important effect on both the bandwidth and the isolation and the simulation results are illustrated in Fig. 5 (b). It can be seen that the mutual coupling is reduce when a3 increases from 2.3mm to 2.5mm. When a3 continues to increase, both the isolation is deteriorated since the a3 changes the dimensions of the M-shaped patch and the U-shaped patch of the 3-D meta-material cells, which alters the resonance characteristics of the meta-material. The parameter h1 and h2 affect the impedance bandwidth and the mutual coupling and their performance is shown in Figs. 5 (c) and (d), respectively. When h1 increases from 0.8mm to 0.9mm, the shorted pins are increased, which increase the inductance of the 3-D meta-material. Thus, the center resonance frequency of the 3-D meta-material shifts to the high frequency, and hence, the mutual coupling is also increased. The parameter h2 control the distance between the top of the 3-D meta-material and the top surface of the FR-4 substrate. With the increment of h1 and h2, the 3-D meta-material is pushed to the direction of the ground plane of the MIMO antenna, which also increases its equivalent capacitance. Thus, the center frequency and the isolation of the MIMO antenna are affected. Thus, we can optimize the parameters of the 3-D meta-material to select the proper dimensions to obtain an optimal performance.

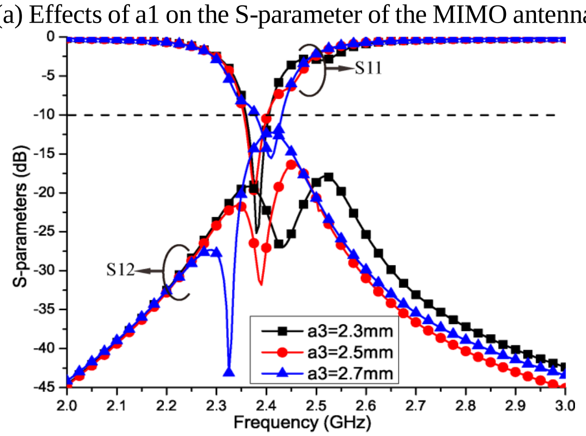
The optimized antenna is fabricated and measured in an anechoic chamber. The fabricated prototype of the MIMO antenna with the proposed embedded 3-D meta-material is shown in Fig. 6 and the measured results are given in Fig. 7. It can be seen that the measured results agree well with the simulated ones. The proposed MIMO antenna operates at 2.4 GHz band, and it also shows a low mutual coupling of -35 dB. Thus, the proposed MIMO antenna with 3-D meta-material achieves an isolation improvement of 18 dB in comparison of the simulated MIMO antenna without the proposed meta-material structure. The differences between the measured and simulated results may be caused by the fabrication errors. The Envelope correlation coefficient (ECC) is also given in Fig. 7 to discuss the mutual coupling of the MIMO antenna. Herein, the ECC of a two-port MIMO antenna in a uniform propagation environment is given by [12]:

$$\rho_e = \frac{\left|S_{11}^{*}S_{12} + S_{21}^{*}S_{22}\right|}{\left(1-\left(\left|S_{11}\right|^2+\left|S_{21}\right|^2\right)\right)\left(1-\left(\left|S_{22}\right|^2+\left|S_{12}\right|^2\right)\right)}.$$

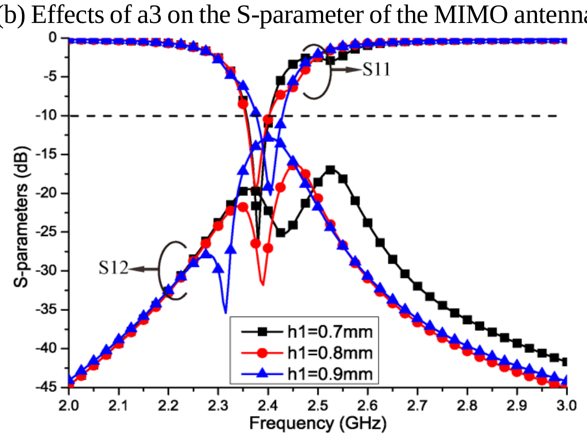
We find that the ECC is almost zero at 2.35 GHz to 2.42 GHz, which means that the two antennas are irrelevant. Thus, our proposed 3-D meta-material structure effectively reduces the mutual coupling and helps to improve the isolation between the two antenna elements. The measured radiation patterns at center operating frequency are shown in Figs. 8 (a) and (b). It is found that the MIMO antenna has directional radiation patterns in both XOZ- and YOZ-planes. Some deviations from the measured and simulated radiation patterns arise from the errors in fabrication and experiment. The gain of the MIMO antenna array is 5 dBi in the center of the operation band.



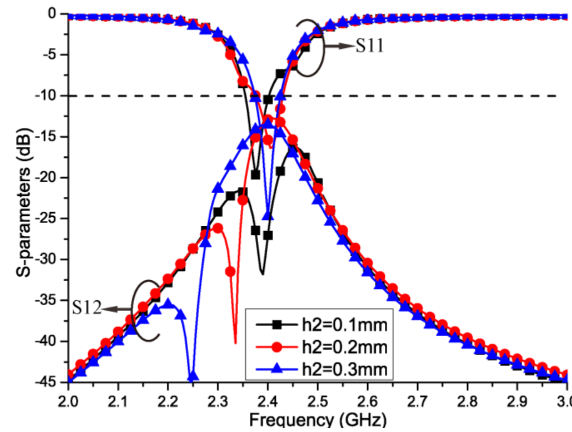
(a) Effects of a1 on the S-parameter of the MIMO antenna



(b) Effects of a3 on the S-parameter of the MIMO antenna



(c) Effects of h1 on the S-parameter of the MIMO antenna



(d) Effects of h2 on the S-parameter of the MIMO antenna

Fig. 5. Parameter effects on the MIMO antenna.

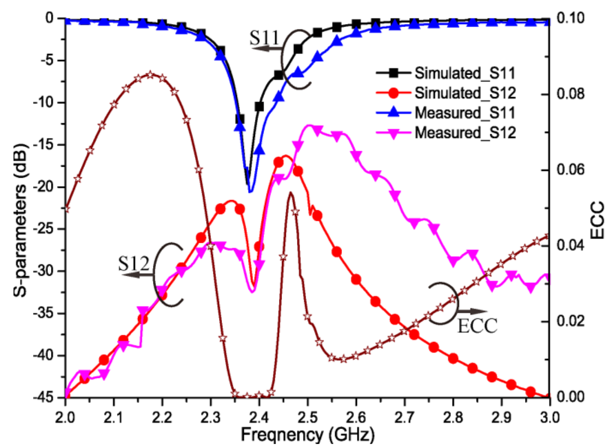
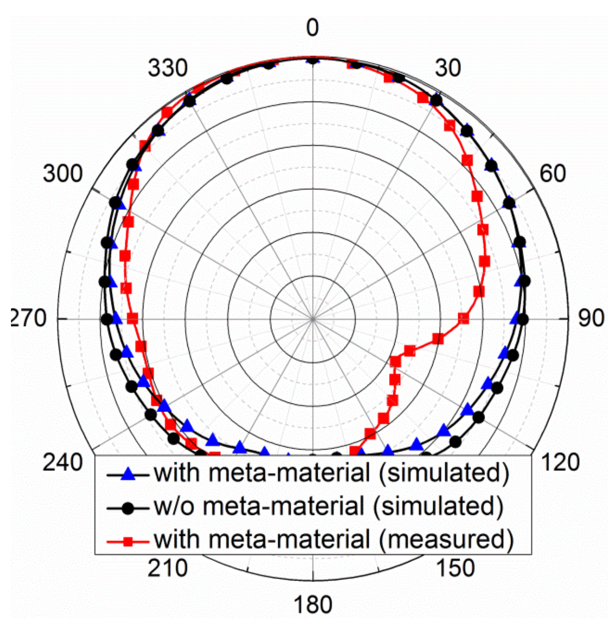
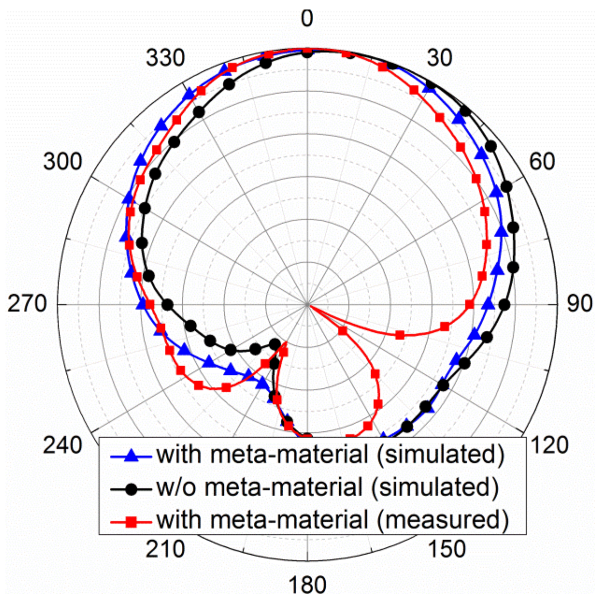


Fig. 7. Performance of the fabricated antenna.



(a) XOZ plane



(b) YOZ plane

Fig. 8. Radiation patterns of fabricated antenna.

IV. CONCLUSION

A 3-D meta-material structure has been proposed and it has been integrated into a MIMO antenna to reduce the mutual coupling between two rectangle patch antennas. The proposed 3-D meta-material cell is a two-layer connected by the shorted pins. The 3-D meta-material cell has been investigated to catch its characteristics. Then, five 3-D meta-material cells have been incorporated into a MIMO antenna with a distance of $0.13\lambda_0$ to improve the isolation. Both the numerical and experimental results showed that more than 18 dB mutual coupling reduction has been obtained without affecting the operating bandwidth and radiation characteristics. Furthermore, the proposed 3-D meta-material structure has a flexible and adjustable characteristic, which can easily integrate into antenna array to improve the isolation.

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