A Low Mutual Coupling Two-Element MIMO Antenna with a Metamaterial Matrix Loading

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Abstract **─** A low mutual coupling two-element multiple-input multiple-output (MIMO) antenna with a loading metamaterial structure is proposed numerically and experimentally. The proposed MIMO antenna operating at 5.5 GHz consists of a two-element patch antenna array and a metamaterial structure which is to reduce the coupling between the two patch antenna elements for a small radar applications. In this design, the edge-to-edge distance between two patch elements is set to be 2 mm, which is closely installed and uses the same ground plane. The proposed metamaterial structure blocks the propagation of the electromagnetic waves from the original propagation path along the substrate. The numerical and experimental results demonstrate that the mutual coupling between the antenna elements is reduced to less than -20 dB in the operating band.

Index Terms **─** Isolation enhancement, metamaterial, MIMO antenna array, mutual decoupling.

I. INTRODUCTION

With the evolution of the advanced wireless communication technologies, the demand of the high data rate, high throughout and high capacity is important to the communication systems, which promote the scholars and industrial companies to develop better communication techniques. Recently, the multiple-input multiple-output MIMO technology and massive MIMO techniques have been seen as the most advantage techniques to improve the communication quality [1-3]. Thus, the MIMO antenna changes to be the important techniques for receiving and transmitting signals. Comparing with the traditional MIMO antenna array technology, the massive MIMO antenna array technology can serve more than hundreds of users and terminals simultaneously, which need to arrange more antenna elements in the limited physical space for the miniaturization of the portable terminals [4-6]. The edge-to-edge distance between the elements in the massive MIMO antenna array is only a fraction of the wavelength, and hence, the mutual coupling in massive MIMO antenna array is inevitable, which will seriously deteriorate the receiving and transmitting signals characteristics of the antenna array [5-6]. In addition, the strong coupling will lead to the signal disturbing from each other antenna element and degrades the maximum achievable performance of the system. Thereby, the mutual decoupling design techniques are required in the practical MIMO or massive MIMO antenna arrays to reject the mutual effects from the neighboring elements.

Until now, there are many existing mutual decoupling techniques used in the MIMO antenna array, including mutual decoupling networking [7-9], defected ground structure (DGS) [10-12], electromagnetic band gap (EBG) [13-15], and metamaterial [16-20], and so on. In [7], mutual decoupling network techniques are adopted and placed between the two neighboring elements in the antenna array, which can reduce the direct coupling but it cannot eliminate the indirect coupling between the elements in the antenna array. In addition, the mutual decoupling networks proposed in [8] are loaded between two-element antenna array, which is difficult to be expanded in massive MIMO antenna array. The DGS reported in [10-12] changes the electric current path in the public metaled ground plane, which can effectively reduce the mutual coupling between the antenna array elements, while it may increase the back radiation and electromagnetic leak. For the EBGs studied in [13-15], they are installed between the antenna array elements, which can provide

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a high impedance characteristic to reject the electromagnetic wave propagation from adjacent antenna array elements. However, this method placed the EBG and the antenna elements on the same substrate to suppress the propagation of the surface waves, resulting in large edge-to-edge distance. Recently, the metamaterial has attracted more attention owning to its unique characteristics like the high impedance within the operation band [16-20]. Then, the metamaterial has been widely studied to create meta-surface to implement the mutual coupling reduction in the MIMO antenna array [21-22]. However, they cannot get ideal matching to the original antenna array. On the other hand, the metamaterial can be regarded as an EBG structure by using its high impedance characteristic in the operating band [22]. The metamaterial can also be used to enhance the antenna gain [23].

In order to expand the meta-surface to mutual decoupling in the massive MIMO antenna array and to furture reach the great matching to original antenna array, the periodic metamaterial is designed as a frequency selective surface by integrating the modified split-ring resonators (SRRs) and metal grid [24]. However, it has a complex structure because the frequency selective characteristics obtaining from the resonant between the modified SRRs which are placed on different layers.

In this paper, the modified SRRs and SRRs are used to construct a meta-surface to reduce the mutual coupling between a two-element MIMO antenna array, which is modeled and optimized in the HFSS based on the finite element method (FEM). Comparing with the traditional one, the proposed meta-surface decoupling is covering to the top of the MIMO antenna array with a distance of 2 mm to make the antenna array much more compact. The proposed antenna array is operated at 5.5-5.75 GHz for small medical radar and WiMAX applications. In this design, the edge-to-edge distance between two patch elements is set to be 2mm, which is closely installed and uses the same ground plane. To further investigate the decoupling function of the proposed meta-material structure in the MIMO antenna array design, a meta-surface (with 4×6 cells) is designed with the same size of the antenna array and is used to realize the coupling reduction. In comparison with the traditional mutual decoupling techniques, this work has follow features:

(1) The proposed meta-material structure is realized based on modified SRRs, making them easy to design.

(2) The proposed meta-material structure has a great impedance matching to the MIMO antenna array, resulting in very small edge-to-edge distance between two patch elements.

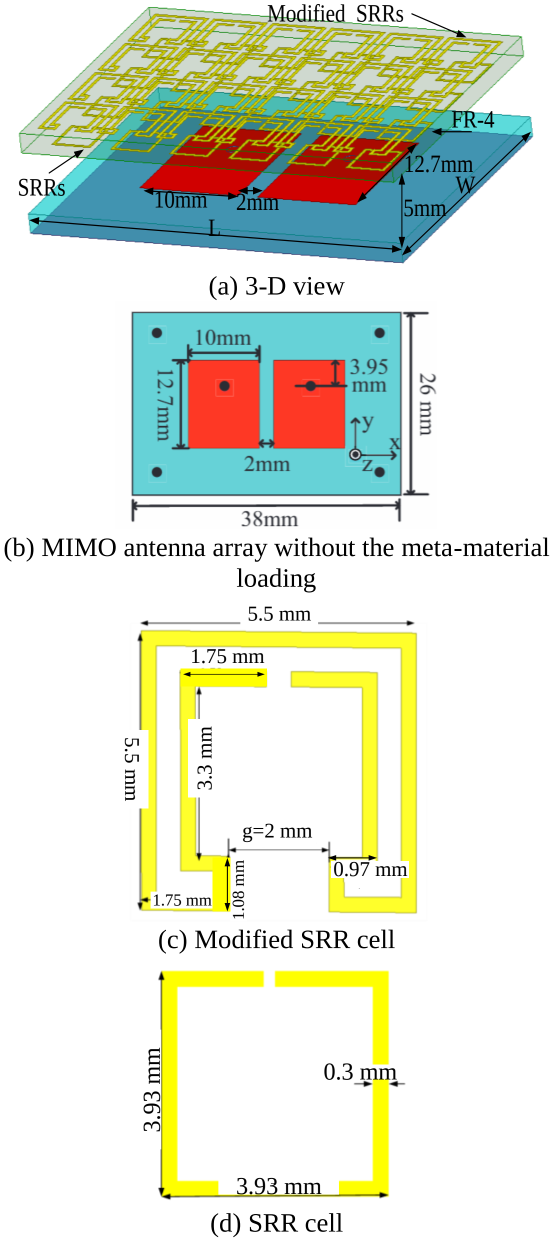
(3) The proposed meta-material structure is designed on the same substrate with two different SRR layers to provide a stable bandwidth of the meta-material.

(4) Since the edge-to-edge distance between the neighboring elements of the antenna array is set to be 2mm, the proposed mutual coupling reduction scheme can be easily integrated in the massive MIMO antenna arrays.

II. THE GEOMETRAY OF THE PROPOSED MIMO ANTENNA ARRAY

The proposed MIMO antenna array is presented in Fig. 1. We can see that the two patch antenna elements are printed on a FR-4 substrate with a thickness of 1.6mm, a relative permittivity of 4.4 and a loss tangent of 0.02, while there is a ground plane on the other side of the MIMO antenna. A meta-material structure is realized by printing the modified SRRs on the top of the second FR-4 substrate, while the SRRs are designed on the bottom of the second substrate to help to expand the operating bandwidth of the meta-material. Then, the developed meta-material structure is installed above the designed MIMO antenna array with a gap of 5 mm between the bottom of meta-material structure and the top of the MIMO antenna array. In this design, the meta-material structure aims to block the space-wave propagation and reduces the mutual coupling of the antenna array. The proposed MIMO antenna is fed by probes, which is connected by using the SMA connectors.

From Fig. 1, we can see that the proposed meta-material structure is realized by a 6×4 meta-material cell matrix, which can cover the entire area of the MIMO antenna array. The principle of the proposed MIMO antenna array scheme is listed in Fig. 2. If one of the antenna is used as the source of the MIMO antenna, there will be induction currents distributed on the near-by antenna element since the distance of these antenna elements are short. Then, the mutual coupling will be happened between the antenna elements. The proposed 6×4 meta-material matrix loading on the top of the MIMO antenna array proposed a high impedance band to suppress the interferences from the near-by antenna elements. To better understand the performance of the meta-material structure and the mutual coupling reduction results, the simulated surface current distribution without and with proposed 6×4 meta-material matrix loading are presented in Fig. 3. Without the proposed 6×4 meta-material matrix, one can see that a strong induction current appears on the right patch antenna when the left patch antenna is exited. In contrast, with the proposed 6×4 meta-material matrix loading, the current on the right patch antenna is very weak. Thus, it is concluded that the suspended 6×4 meta-material matrix can effectively reduce the mutual coupling between antenna array elements.



(a) 3-D view

(b) MIMO antenna array without the meta-material loading

(c) Modified SRR cell

(d) SRR cell

Fig. 1. Geometry of the proposed MIMO antenna array.

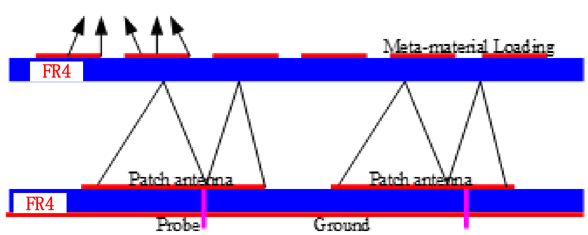


Fig. 2. Radiation principle of the proposed MIM (the block lines are the wave propagation path and the arrows are the directions of the radiation).

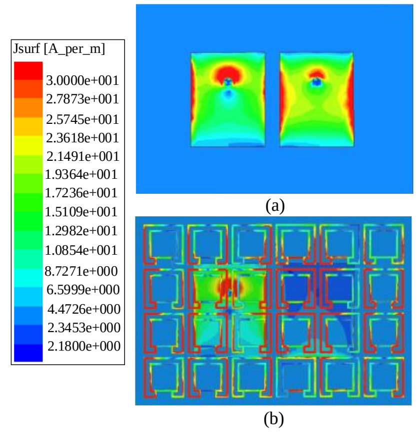
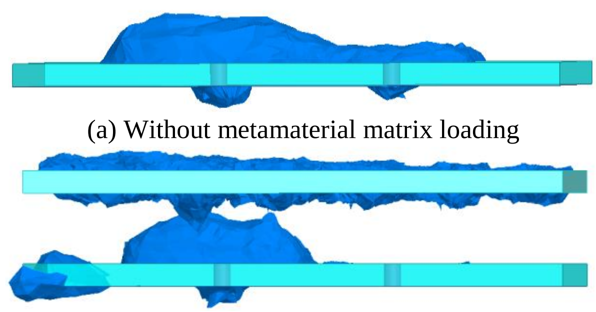


Fig. 3. Surface current distribution of the proposed MIMO antenna array for 5.5 GHz at time of 0: (a) without metamaterial matrix loading, and (b) with metamaterial matrix loading.



(a) Without metamaterial matrix loading

(b) With metamaterial matrix loading

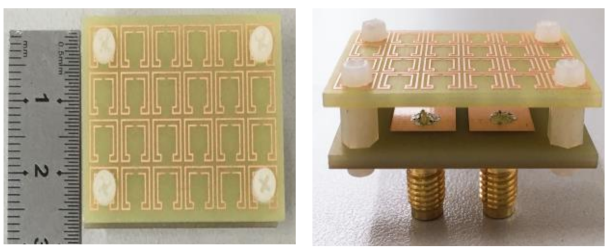
Fig. 4. Calculated electric field distributions of the MIMO antenna array.

To further discuss the above phenomena, the electric field distributions of the proposed MIMO antenna array without and with the proposed 6×4 meta-material matrix loading are shown in Fig. 4. Herein, two antennas in the array are fed together and the results are obtained using the HFSS. We can see that without the 6×4 meta-material matrix loading, a large amount of electric field is coupled to the right patch antenna from the space propagation. Conversely, the electric field is directed toward the broadside direction when the proposed 6×4 meta-material matrix loading is used as a cover.

III. RESULTS AND DISCUSSIONS

From the optimization of the MIMO antenna array based on the HFSS, the finalized MIMO antenna array has been fabricated and measured in a chamber. Figure 5 shows the fabricated MIMO antenna for top and side view. Also, the measurement setup of the MIMO antenna array in the chamber is also given and presented in Fig. 6.

The measured S-parameters, including the reflection coefficient (S11) and isolation (S12) are presented in Fig. 7. We can see that the proposed MIMO antenna integrated with the proposed 6×4 meta-material matrix loading has almost the same impedance bandwidth, meaning that the proposed 6×4 meta-material matrix loading scheme does not affect the performance of the MIMO antenna. However, we can see that the isolation has been improved by more than 20dB via the 6×4 meta-material matrix loading. Thus, the mutual coupling of the MIMO antenna array has been reduced to be less than -20dB. This is because that the proposed 6×4 meta-material matrix loading can block the space-wave propagation. There are some differences in between the measured and simulated results, which is caused by the instable of the FR-4 substrate, fabrication tolerance error and measurement errors. Herein, the fabrication tolerance error might be the main effects on the measured results.



(a) Top view (b) Side view

Fig. 5. Photograph of the fabricated prototype.

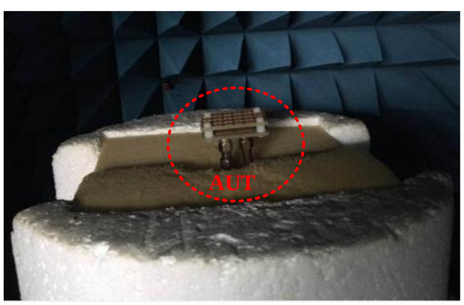


Fig. 6. The measurement setup of the MIMO antenna array in the chamber (AUT: Antenna under test).

Figure 8 shows the radiation patterns of the proposed MIMO antenna array. The radiation patterns at E-plane and H-plane have some difference, which might be caused by the asymmetry of the meta-material array effects. The simulated 3D radiation patterns of the proposed antenna array is preeented in Fig. 9. The obtained radiation patterns show that the proposed antenna has directional-like radiation patterns owning to the effects of the meta-material loading. However, its radiation patterns are similar to that of the directional patch antenna. Thus, the loaded 6×4 meta-material matrix loading can also enhance the gain of the MIMO antenna because the meta-material matrix aided in concentrating more energy into the band-pass frequency band. The measured radiation efficiency is 66%, the measured gain is 4.65 dBi and the measured ECC is less than 0.015.

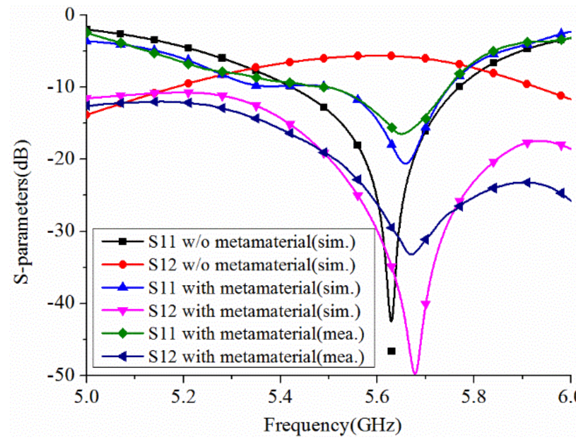


Fig. 7. The simulated and measured S-parameters.

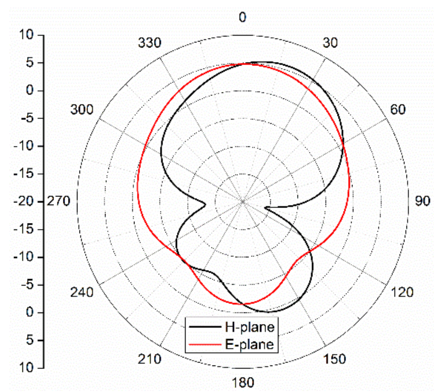


Fig. 8. The radiation patterns of the MIMO antenna array at 5.5 GHz.

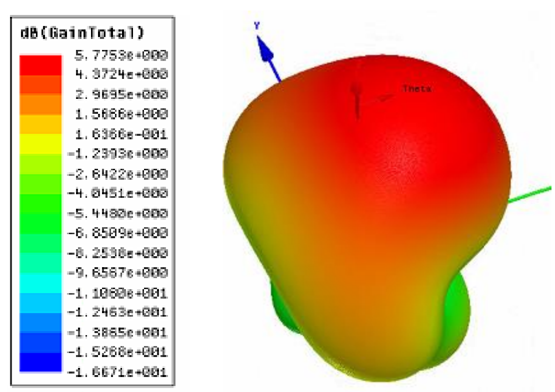


Fig. 9. The simulated 3D radiation patterns of the proposed antenna array at 5.5 GHz.

To prove the advantage of the designed MIMO antenna array, the performance of the proposed MIMO antenna array is compared with the state-of-the-art in Table 1. From the Table 1, it can be found that the proposed MIMO antenna has the small size, high gain and efficiency.

Table 1 Comparison of the proposed MIMO antenna array

Ref.	10-dB BW	Size (mm^2)	Ios. Enhance (dB)	Peak ECC/Gain	Eff. (%)
[7]	9.5%	40×40.4	33	NA/6.55	NA
[11]	1.9%	36×36	12	NA/NA	NA
[17]	1%	70×30	11	NA/4.37	NA
PW	4.4%	38×26	25	0.015/4.65	66

Notes: PW: Proposed work; Iso.: Isolation; ECC: envelope correlation coefficient.

IV. CONCLUSION

A high isolation two-element MIMO antenna array has been proposed by using a 6×4 meta-material matrix loading technique and its performance has been investigated and discussed numerically and experimentally. The proposed MIMO antenna array is optimized, fabricated and measured to verify its performance, while the results demonstrate that the isolation of the proposed MIMO antenna array is less than -20 dB within the operating band. In the future, the proposed technique can be used for developing the dual-band or dual-polarization low mutual coupling MIMO arrays [25-26], beamforming [27], direction of arrival (DOA) [28-29] using adaptive methods [30-36].

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