International Journal of Microwave and Wireless Technologies

cambridge.org/mrf

Gain enhancement for MIMO antenna using metamaterial structure

Nguyen Ngoc Lan and Vu Van Yem

School of Electronics and Telecommunications, Hanoi University of Science and Technology, Hanoi, Vietnam

Research Paper

Cite this article: Nguyen NL, Vu VY (2019). Gain enhancement for MIMO antenna using metamaterial structure. *International Journal of Microwave and Wireless Technologies* **11**, 851–862. https://doi.org/10.1017/S175907871900059X

Received: 12 September 2018
Revised: 16 April 2019
Accepted: 17 April 2019
First published online: 15 May 2019

Key words:
Array antenna; metamaterial antenna; MIMO antenna; mutual coupling

Author for correspondence:
Nguyen Ngoc Lan, E-mail: nnlan@moet.edu.vn

Abstract

In this paper, a multiple input multiple output antenna which operates at 5.8 GHz for wireless local area network applications is proposed. The proposed antenna is composed of two sets of four elements antenna array (2 × 2) on the top and a novel metamaterial structure on the ground plane. Here, the ground plane, which includes a lattice of 2 × 5 unit cells of metamaterial structure, is utilized in order to improve parameters of the antenna. Thanks to the proposed metamaterial structure, not only gain and bandwidth of antenna are enhanced, but also mutual coupling is reduced. The final design, with an overall size of 137 × 77 × 3.048 mm^3, resulted in a $|S11| < -10$ dB bandwidth of 1.78 GHz and a peak gain of 9.2 dBi. In addition, the isolation is higher than 18 dB although the close separation from edge to edge of the two antennas is only 2 mm and radiation efficiency of 73% at the operating frequency band. All is simulated based on CST Studio software and the simulated S-parameter results of the antenna are in good agreement with measurement results.

Introduction

In recent years, the rapid development of the wireless local area networks (WLAN) has opened a new age, where the demand for high data rates and high reliability is extremely urgent. Multiple input multiple output (MIMO) communication technology has received much attention from researchers in the world thanks to its advantages, for example high data rate, high reliability, and high spectral efficiency. MIMO technology has been considered the best solution for most of the problems in wireless communication [1]. However, due to space limitation, the separation between antenna elements in MIMO systems is often small, leading to considerably large mutual coupling between them. Mutual coupling between elements in the array not only affects the antenna efficiency but also influences the correlation [2]. The phenomenon of mutual coupling is considered as a bottleneck in the MIMO systems, and therefore, it is an urgent issue that needs to be solved. The easiest way to cancel mutual coupling is to increase the physical distance between elements. However, this leads to an increase in their occupied space. Therefore, this is not an optimized method. Currently, one of the most used solutions to improve mutual coupling for antenna is utilizing metamaterial structure thanks to its unique electromagnetic characteristics [3].

From other aspects, microstrip patch antennas are the best choice in many existing and future wireless communication systems [4–6] because of its advantages such as small size, lightweight, easy fabrication, and low cost. However, they mainly suffer from performance limitations, for example narrow bandwidth, low gain, and low efficiency. Therefore, the improvement of the parameters for antenna is necessary. Different solutions have been adopted to improve the antenna parameters, for instance, gain enhancement including reflective surface [7], metamaterial [8]; bandwidth enhancement consisting multiple substrate [9], defected ground structure (DGS) [10], and so on. Each method is based on its own principle. While the method of reflective surface enhances gain based on reflection principle to reduce side lobe and back lobe, utilizing metamaterial improves gain by current re-distribution. Similarly, an increase of thickness of substrate and creation of consecutive cavity resonators are rules to enhance bandwidth for antenna by using multiple substrate and DGS, respectively. Many works have been conducted to improve parameters for antenna such as: using meander line resonators [11], electromagnetic band gap [12], metamaterial [13], DGS [14]. However, the mutual coupling in these papers is still large. For example, the isolation between elements in an array is only 16 dB in [11]. Similarly, although the gain of the antenna is quite high, the isolation is not good (−15 dB) [12]. This issue also appears in papers of [13, 14]. With these isolations, antennas cannot operate well. Moreover, in other documents [15, 16], the parameters including gain and bandwidth of antennas are not enough to satisfy for applications. This shows that the simultaneous improvement of antenna parameters is not easy.

For this reason, this paper proposes a new metamaterial structure with a simple configuration, compact size, and planar in order to improve parameters for the antenna. The proposed structure is applied for a MIMO antenna including two sets of four elements (2 × 2). It is

© Cambridge University Press and the European Microwave Association 2019

CAMBRIDGE UNIVERSITY PRESS

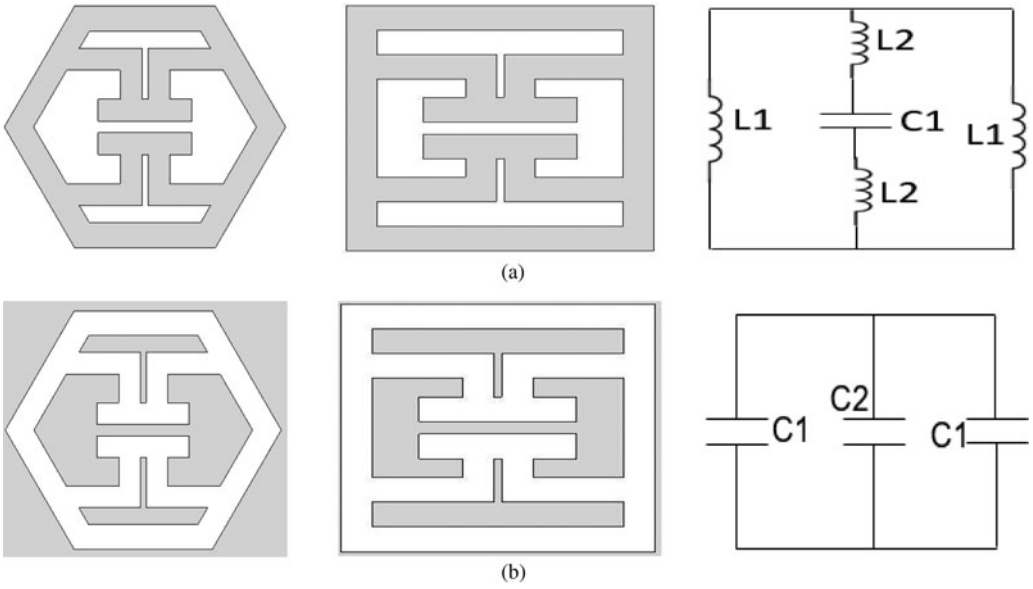


Fig. 1. The model of the metamaterial structure: (a) the proposed structure, (b) the compensation structure.

observed that the antenna operates at 5.8 GHz with the bandwidth of 1.78 GHz. In addition, the MIMO antenna is constructed with close separation of 2 mm from edge to edge thanks to a novel metamaterial structure, the mutual coupling between elements are under −18 dB. Besides, the antenna provides a high gain (9.2 dBi). The antenna has been characterized numerically using the CST Studio Suite and verified by measurements.

The proposed antenna array

The proposed metamaterial structure

Firstly, the model of the proposed metamaterial structure and its equivalent circuit are shown in Fig. 1. This idea is started from the structure of OE2 in [17] and [18]. By the development in the shape of structure, the paper obtained a new configuration as shown in Fig. 1. Besides, to increase the value of L and C, this paper utilizes folded microstrip lines and this leads to reduce the frequency for the antenna. This is also one of the methods to minimize the size for the antenna. The radius of the proposed structure is 8.5 mm while the size of the substrate is $18 \times 20 \times 3.048$ mm^3.

Here, the equivalent circuits are generated based on the rule: the gaps between two microstrip lines make equivalent capacitance C while the inductances are introduced by microstrip lines. The proposed structure is planar. It is, therefore, easy for fabrication and design. Using both the compensation structure and the proposed structure help to make various about capacitances (C) and inductances (L). This leads to an ease in optimization to reach the better parameters for the antenna.

In order to confirm the proposed structure is metamaterial, the paper sets up a simulation including a microstrip transmission line of 50 Ω and the proposed structure on ground based on a substrate of Roger4350B with a thickness of 1.524 mm, $\varepsilon_r = 3.66$, and tan $\delta = 0.0037$. The proposed structure is designed for WLAN application at the central frequency of 5.8 GHz. By utilizing for the formulas in [19], we can calculate the dielectric constant and the permeability from S-parameters. The model of the simulation and its S-parameters are shown in Fig. 2 while the simulation results (the impedance (z), the refractive index (n), the dielectric constant (ε), and the permeability (μ)) are illustrated in Fig. 3.

From Fig. 3, we can see that μ and ϵ are simultaneously negative in a frequency range from 4.5 to 7 GHz. This shows that the proposed structure is metamaterial and it supports a frequency range of 5.8 GHz.

Design of array antenna

The structure and model of the proposed antenna are shown in Fig. 4. Initially, a single array is realized for operating at a frequency band of 5.8 GHz. The antenna consists of an array antenna on top in the first substrate, second substrate, and ground layer with metamaterial structure on the bottom. The selected dielectric material is Roger4350B with parameters: $h = 1.524$ mm, $\varepsilon_r = 3.66$, and tan $\delta = 0.0037$. To increase gain for antenna, this paper uses two patches and they are placed next to each other with the closest distance between them is 0.5 mm. The array includes four elements and three T-junction power dividers. In this case, the power divider is considered as a three-port network with one input and two outputs. Moreover, these are equal dividers, and therefore, the powers at port 2 and 3 are half the one of port 1. This means that the parameters of $S21$and $S31$ are −3 dB. In addition, to match impedance for power dividers, transformers of $\lambda/4$ are used. Then, the impedances of transformers and transmission lines are given:

$$Z = \sqrt{Z_0 \cdot Z_{in}}, \tag{1}$$

$$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_r}} \cdot \frac{1}{\left(\frac{w_f}{h} + 1.393 + 0.677\ln\left(\frac{w_f}{h} + 1.444\right)\right)}. \tag{2}$$

Figure 5 illustrates the model and S-parameters of the power divider. In Fig. 5, we can see that the power divider has large

https://doi.org/10.1017/S175907871900059X Published online by Cambridge University Press

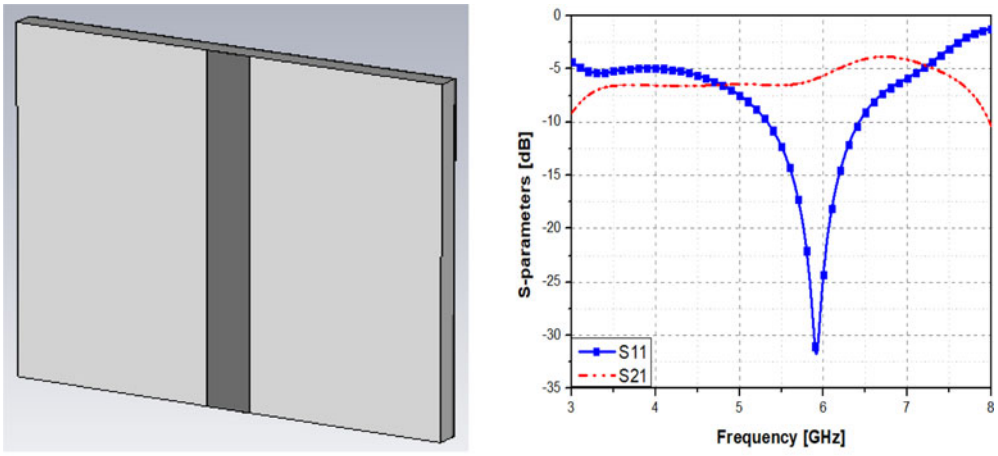


Fig. 2. The model for simulation set-up of the proposed structure.

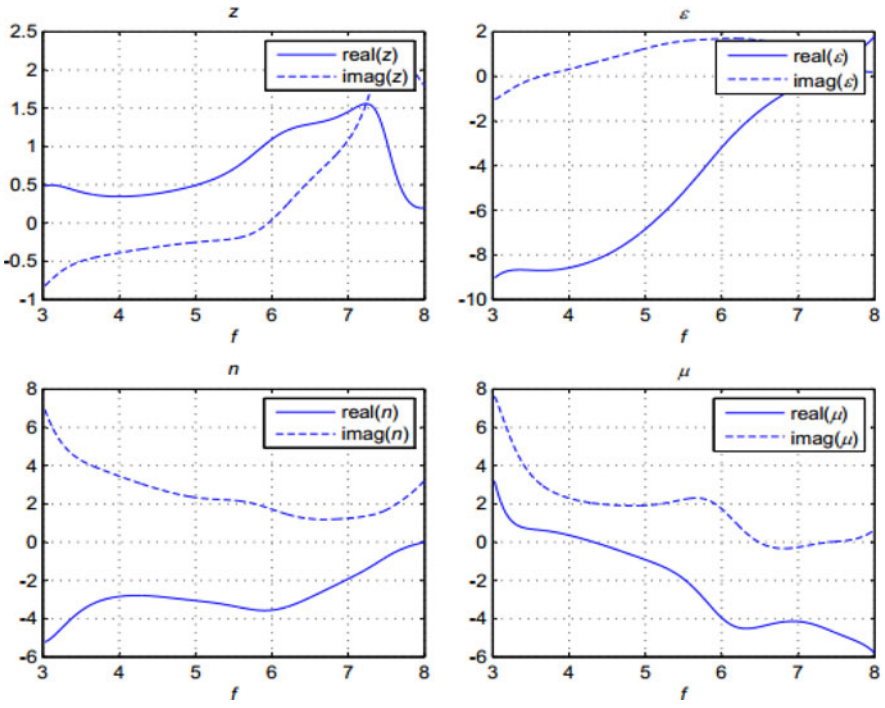


Fig. 3. The results of the simulation set-up.

bandwidth (from 4 to 7.5 GHz) and low return-loss (−47.5 dB). In addition, the values of *S*21 and *S*31 are −3.2 dB.

Here, the distance between elements is approximately 27 mm. The dimension of an element is 8×11 mm^2, while the overall size of the array is $70 \times 72 \times 3.048$ mm^3. Table 1 shows the parameters of the proposed array antenna while Table 2 illustrates the parameters of the power divider.

To enhance gain for antenna, the paper uses metamaterial structure on the ground plane. The equivalent circuit of each cell is indicated in Fig. 1. Here, the capacitor and inductor are given by [20]:

$$C_i = \varepsilon_r \varepsilon_0 \times (A/h), \tag{3}$$

$$L(nH/mm) = 0.2\left[\ln\left(\frac{l}{w+t}\right) + 1.193 + 0.2235\frac{w+t}{l}\right], \tag{4}$$

in which, ε_r and ε_0 are the permittivity of substrate and space, respectively, A is an area of plate ($L \times W$), h is the height of substrate, w and l are the width and length of the ribbon, respectively, and t is the meta thickness.

If the elements are parallel, then the total capacitor and inductor can be calculated as follows:

$$C_{total} = \sum_{i=1}^{n} C_i, \tag{5}$$

$$\frac{1}{L_{total}} = \frac{1}{L_1} + \frac{1}{L_2} + \cdots \frac{1}{L_n}, \tag{6}$$

https://doi.org/10.1017/S175907871900059X Published online by Cambridge University Press

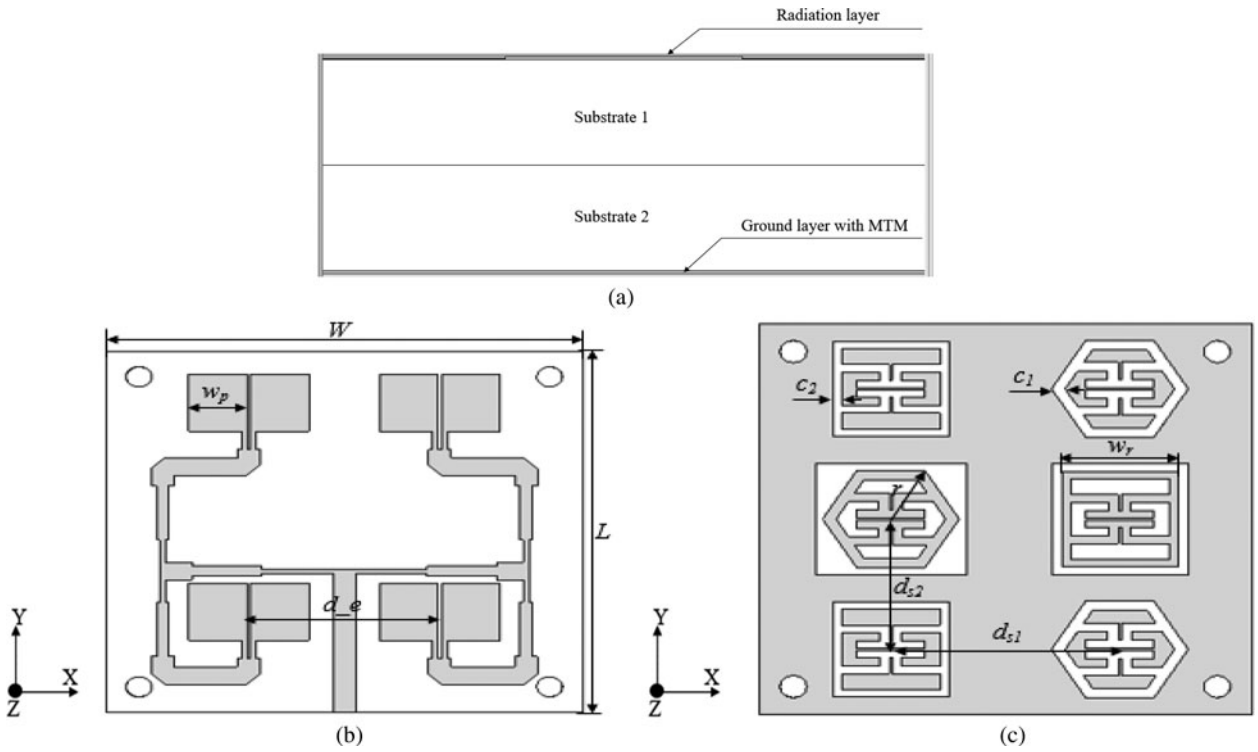


Fig. 4. The model of the proposed array: (a) the structure of the proposed array, (b) front view, (c) back view (dark color for metal and light color for substrate).

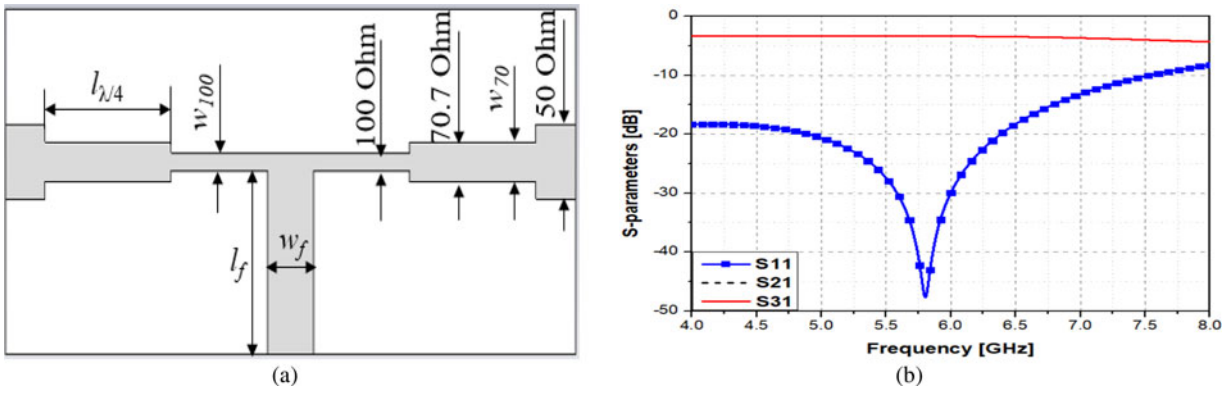


Fig. 5. The model and the parameters of the power divider.

Table 1. Some parameters of the proposed antenna

Parameters	Value (mm)	Parameters	Value (mm)
W	72	L	70
w_p	8	l_p	11
d_e	27	$c1$	2
$c2$	2.6	d_{s1}	16.7
d_{s2}	23.3	r	10

Table 2. Some parameters of the power divider

Parameters	$l_{\lambda/4}$	w_f	w_{100}	w_{70}	l_f
Value (mm)	9.5	3.45	0.84	1.85	8.5

while the elements are series:

$$\frac{1}{C_{total}} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots \frac{1}{C_n}, \tag{7}$$

$$L_{total} = \sum_{i=1}^{n} L_i. \tag{8}$$

Finally, the resonant frequency is given by

$$f_{re} = \frac{1}{2\pi f \sqrt{L_{total} C_{total}}}. \tag{9}$$

https://doi.org/10.1017/S175907871900059X Published online by Cambridge University Press

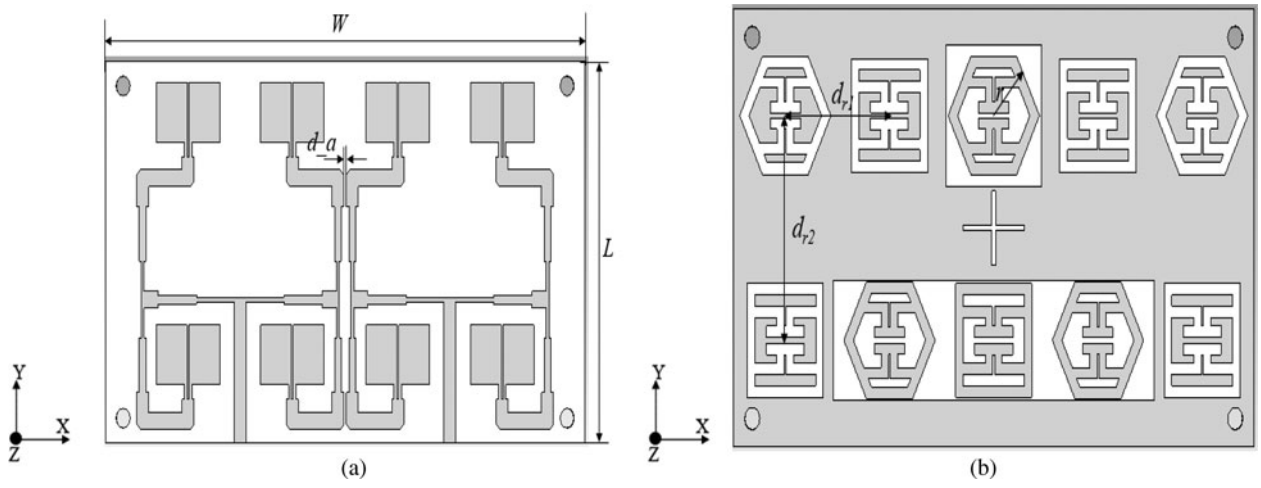


Fig. 6. The model of the MIMO array antenna: (a) top view, (b) bottom view.

Table 3. The parameters of the proposed MIMO antenna.

Parameter	W	L	d_a	d_{r1}	d_{r2}	r
Value (mm)	137	77	2	19.7	27.4	12

Based on the above formulas, the final dimensions of the metamaterial structure as shown in Table 1 are optimized by CST Studio software. Moreover, the two branches of patches are also used to improve gain for antenna.

Besides, an indispensable component in the array antenna is power dividers. To match impedance for them, the quarter-wave transformers are used, then, the width of the transmission line is given by the expression:

$$Z_0 = \frac{60}{\sqrt{\varepsilon_r}} \cdot \ln\left(\frac{8h}{w_f} + \frac{w_f}{4h}\right) if w/h < 1, \quad (10)$$

or using expression (2) if $w/h > 1$.

Design of MIMO array antenna

The model of the MIMO array antenna is illustrated in Fig. 6. Using Roger4350B substrate with a height of 1.524 mm, $\varepsilon_r = 3.66$, and $\delta = 0.0037$, the MIMO antenna gets a patch dimension of 8×12 mm^2 and overall size of $137 \times 77 \times 3.048$ mm^3. The MIMO array antenna has a symmetric structure including two arrays placing side by side with the closest distance of $d_a = 2$ mm from edge to edge of the two antennas. The proposed antenna includes two arrays, in which each array consists of four elements (2×2).

To improve gain and bandwidth for antenna, metamaterial structure is loaded on the ground plane. We know that the number of cells does not affect the resonant frequency of the antenna. However, this influences parameters of the antenna. Therefore, we have to choose the right number of cells so that the parameters of the antenna are the best. In addition, if the number of cells is too large, the complexity and the time for each task will be increasable. For this reason, the selected number of cells is 10. Here, the radius of the hexagon and the width of the square are 12 and 20 mm, respectively. The distances between cells are approximately 27.4 and 19.7 mm, respectively. The parameters of the proposed MIMO antenna are given in Table 3.

Results and discussions

Simulation results

Single array antenna

Figures 7 and 8 show the reflection coefficient, gain, efficiency, and the radiation patterns of the single array antenna, respectively.

From Figs 7 and 8, we can see that the bandwidth of the single antenna is approximately 330 MHz while the gain reaches 8.24 dBi. Here, the return loss of the antenna at the frequency 5.8 GHz is −24 dB. This indicates that the impedance matching of the antenna is quite good. In addition, the efficiency of the antenna gets 79%. Moreover, the antenna has a high directivity (10.45 dBi) and the low side lobe level (−8.1 dB). It can be seen that that the angular width (3 dB) is only 36.6°.

MIMO array antenna

To illustrate the effect of the proposed metamaterial structure on the parameters of antenna, this paper simulates in some cases: one substrate layer, two substrate layers, and two substrate layers with metamaterial structure.

Firstly, Fig. 9 shows the difference in the reflection coefficient in three cases. It is observed from this figure that there is a dramatical variance in the bandwidth of antenna in the cases where the bandwidth is the smallest when the antenna uses one substrate layer (140 MHz). This is reasonable because the antenna does not use any method to enhance the bandwidth. Therefore, the bandwidth is only one resonant mode. There is a slight improvement in the bandwidth of antenna in the case of the antenna using two substrate layers and this improvement is enhanced from an increase of the substrate height. However, the bandwidth of antenna is still one resonant mode. As a result, the bandwidth is only 250 MHz. When antenna uses two substrate layers with metamaterial structure, there is a significant improvement in the bandwidth of antenna. The bandwidth is not only enhanced from the increase of the substrate, but also from the use of metamaterial structure on the ground plane

https://doi.org/10.1017/S175907871900059X Published online by Cambridge University Press

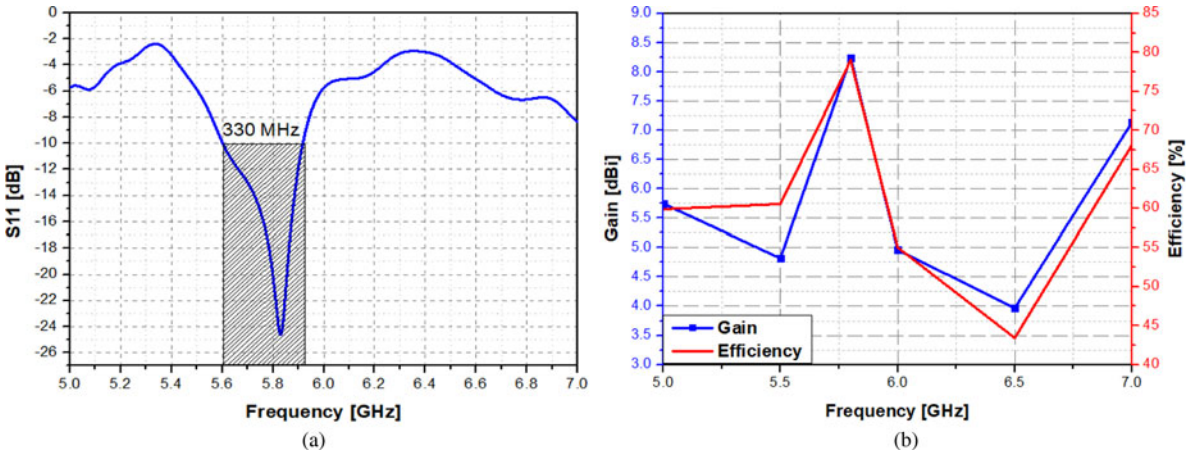


Fig. 7. (a) The reflection coefficient, (b) the gain and efficiency of the single array antenna.

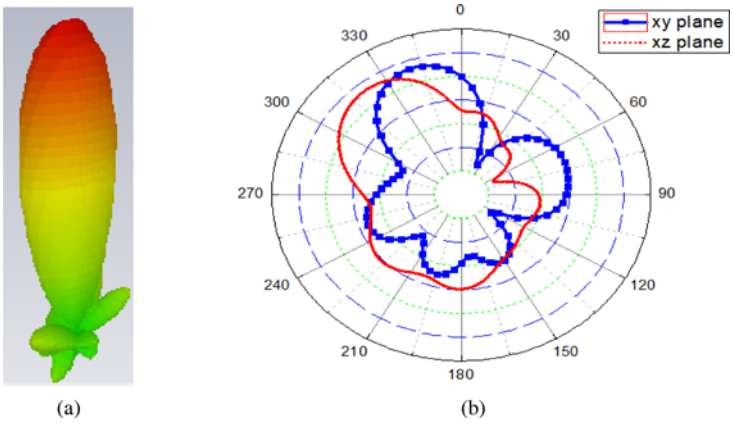


Fig. 8. The radiation pattern of the proposed array antenna: (a) 3D, (b) *xy* and *xz* planes.

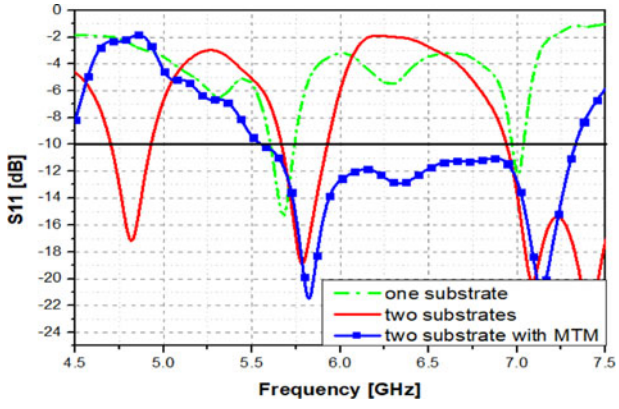


Fig. 9. The difference in the bandwidth of antenna in three cases: one substrate, two substrates, two substrates with MTM.

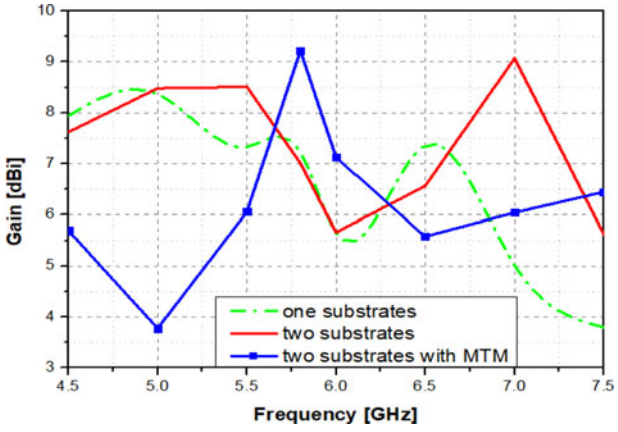


Fig. 10. The difference in the gain of the antenna in three cases: one substrate, two substrates, two substrates with MTM.

through created consecutive cavity resonators. In this case, the bandwidth includes three consecutive resonant modes. Therefore, the bandwidth of antenna reaches 1.78 GHz.

Using metamaterial structure on the ground plane not only improves bandwidth, but also enhances gain for antenna through current re-distribution. This is indicated in Fig. 10.

From Fig. 10, we can see that the gain of the antenna with two substrate layers with metamaterial structure is the highest pick (9.2 dBi) while in another case, the gain values of the antenna are only 7.22 and 7 dBi, respectively. It is clear that the gain of the antenna is significantly improved through current re-distribution. We know that radiation of the microstrip antenna is determined from the field distribution between the patch metallization and ground plane. In other words, the radiation can be described in terms of the surface current distribution on the patch metallization

https://doi.org/10.1017/S175907871900059X Published online by Cambridge University Press

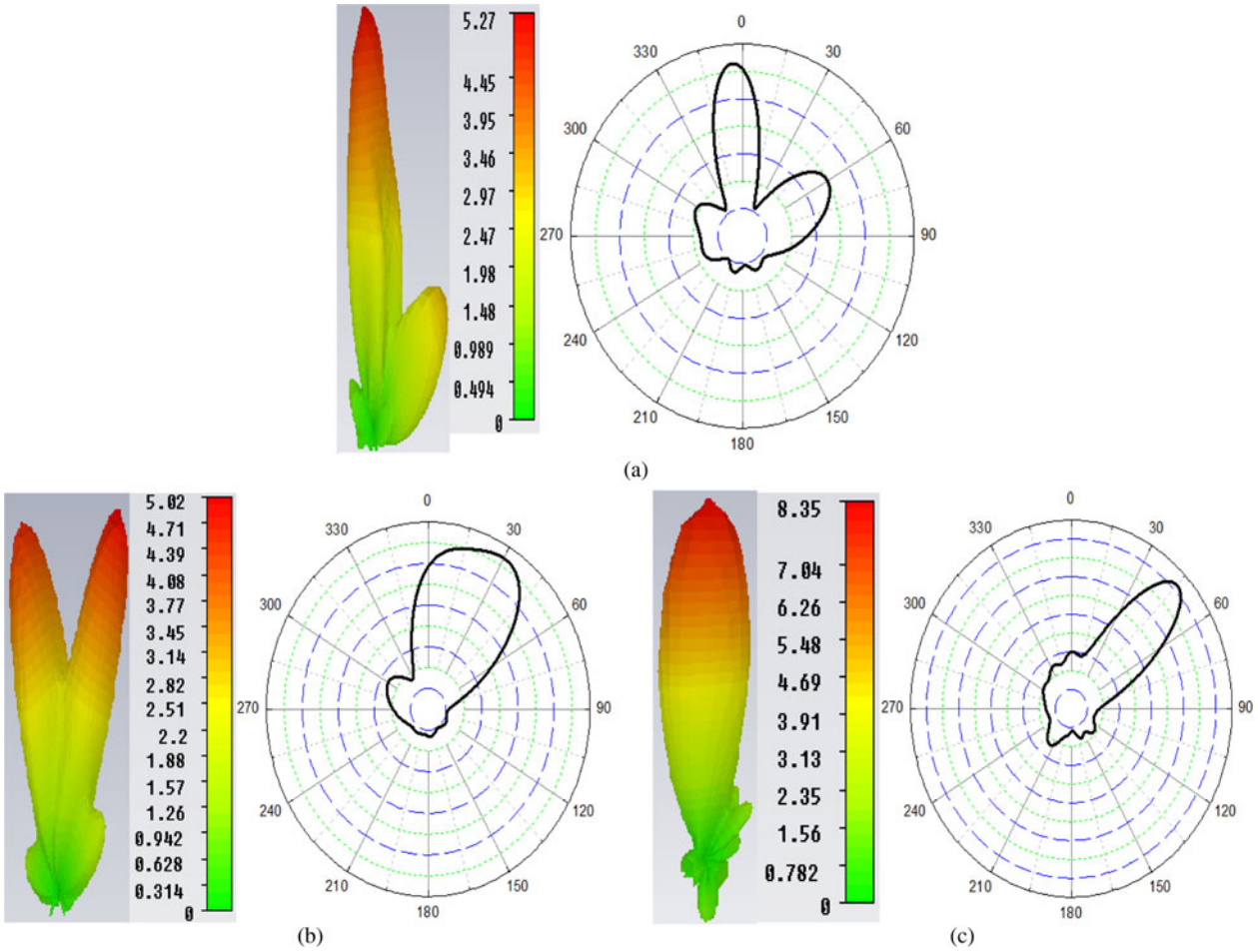


Fig. 11. The difference in the radiation pattern in three cases: (a) one substrate, (b) two substrates, and (c) two substrates with metamaterial.

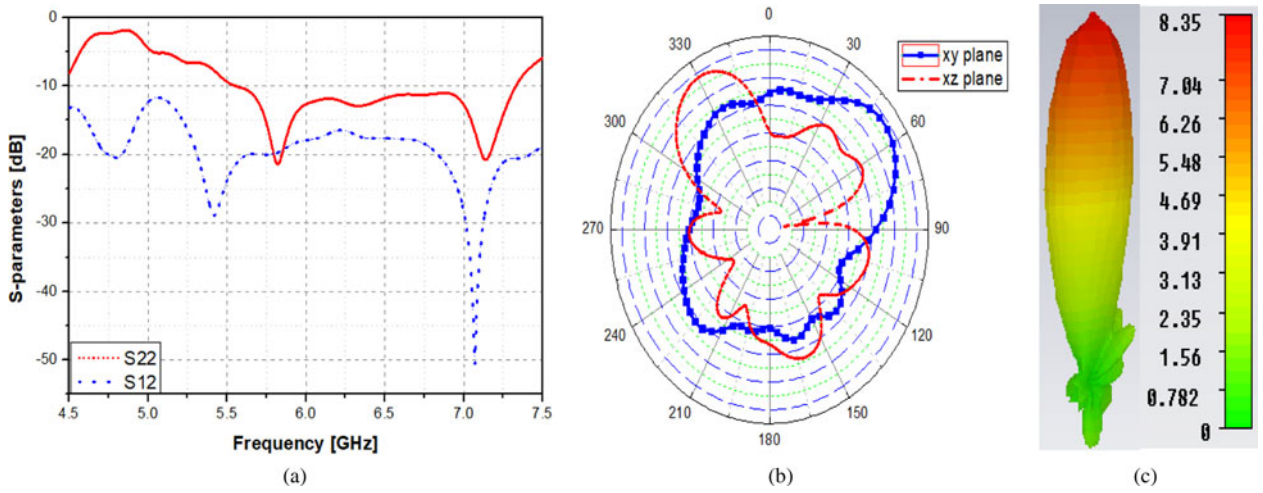


Fig. 12. The simulated results of the proposed MIMO antenna: (a) *S*-parameters, (b) *xy* and *xz* planes, 3D radiation.

[21]. Based on the principle of gain enhancement for antenna using metamaterial structure is found in [22], and using the proposed metamaterial structure causes current re-distribution in antenna and this leads to interference between waves. This opens an opportunity to gain enhancement for the antenna. Here, the gain of the antenna is enhanced when we re-distribute current in order that more and more currents at where the phase shift is 0 (constructive interference) whereas in other places, there is a limitation (deconstructive interference). Then, not only the gain is improved, but also the directivity is still enhanced.

https://doi.org/10.1017/S175907871900059X Published online by Cambridge University Press

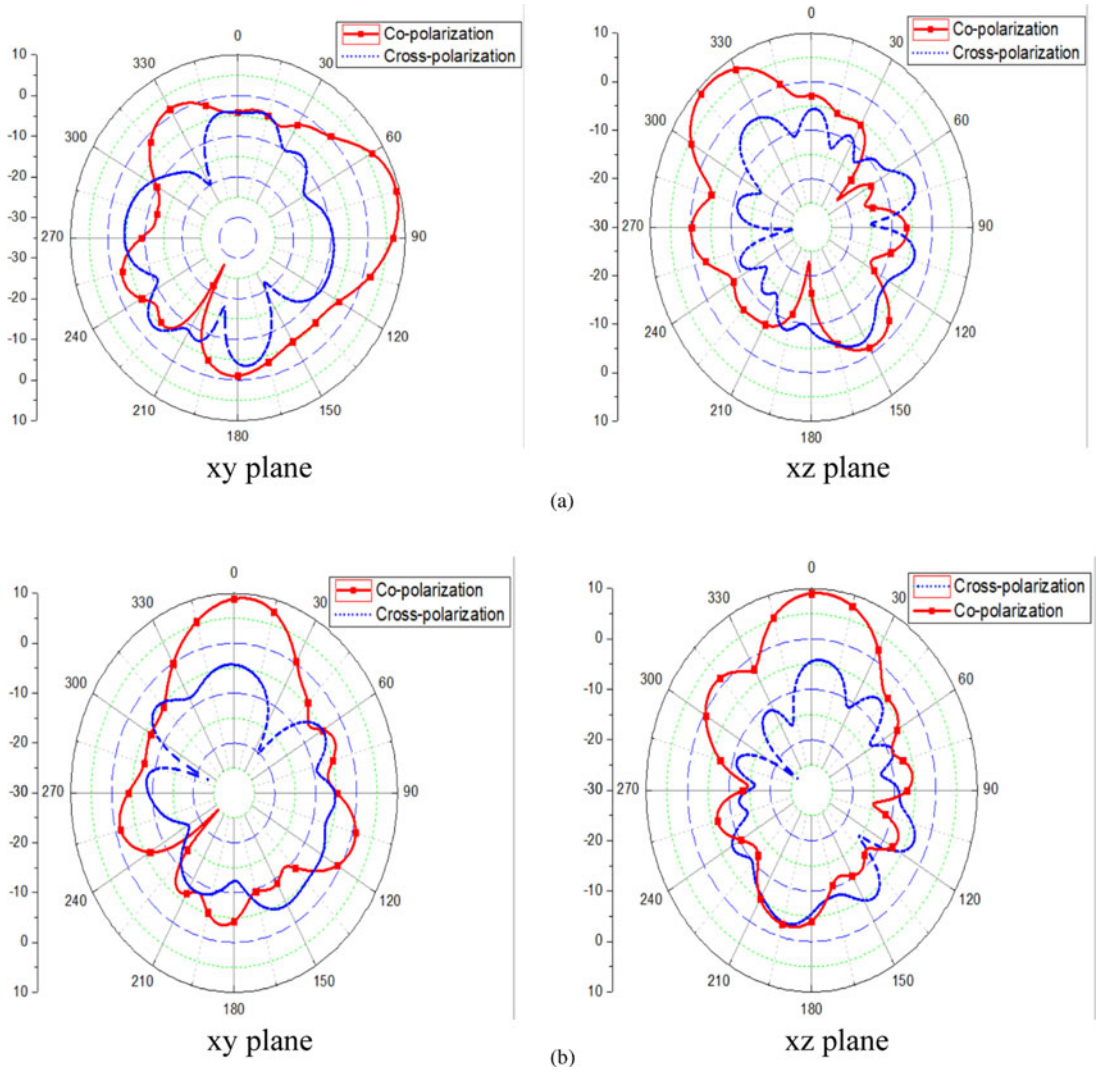


Fig. 13. The normalized 5.8 GHz radiation pattern of the proposed antenna: (a) Port 1, (b) Port 2.

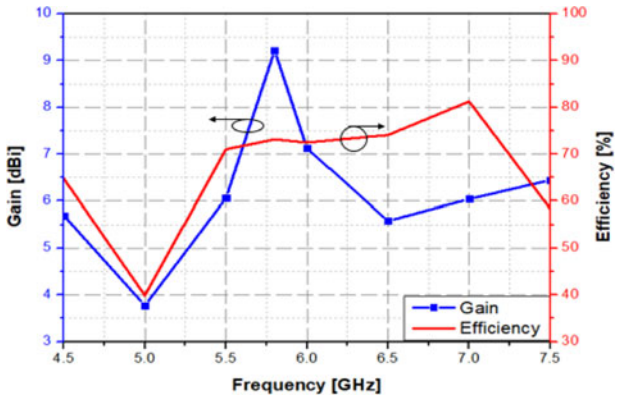


Fig. 14. The gain and efficiency of the proposed antenna.

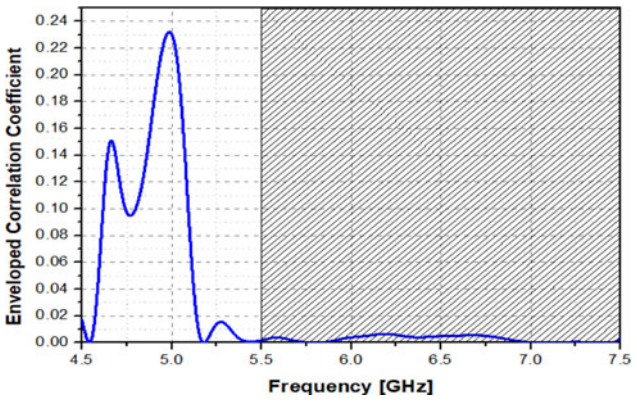


Fig. 15. The ECC of the proposed MIMO array antenna.

Figure 11 shows the difference in the radiation pattern of the antenna in three cases.

It is clear that the difference in the radiation pattern between cases is clear. In two cases of one and two substrates, the directivity of the antenna is very low while the side lobe level is high. These are shown through the values of the main lobe magnitude that are 5.67 and 7.24 dB, respectively, and the side lobe levels are −2.5 and −6.7 dB. When the antenna uses two substrates and metamaterial structure, the parameters of antenna such as the main lobe magnitude and the directivity are 9.18 and 10.45 dBi.

https://doi.org/10.1017/S175907871900059X Published online by Cambridge University Press

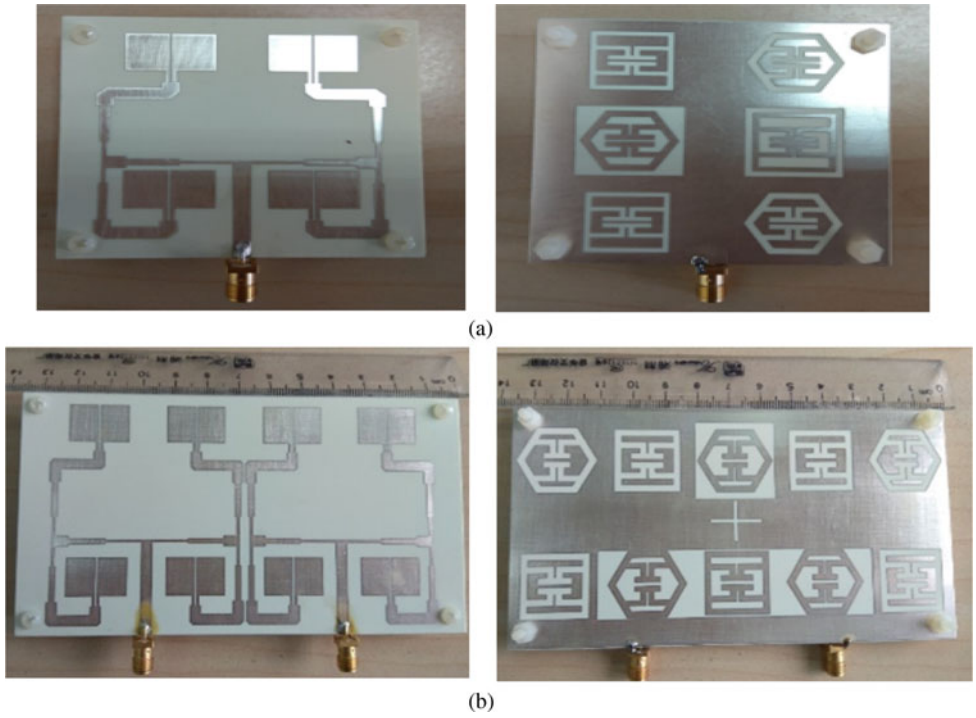


Fig. 16. The prototypes of the proposed MIMO antenna: (a) single array antenna, (b) MIMO array antenna.

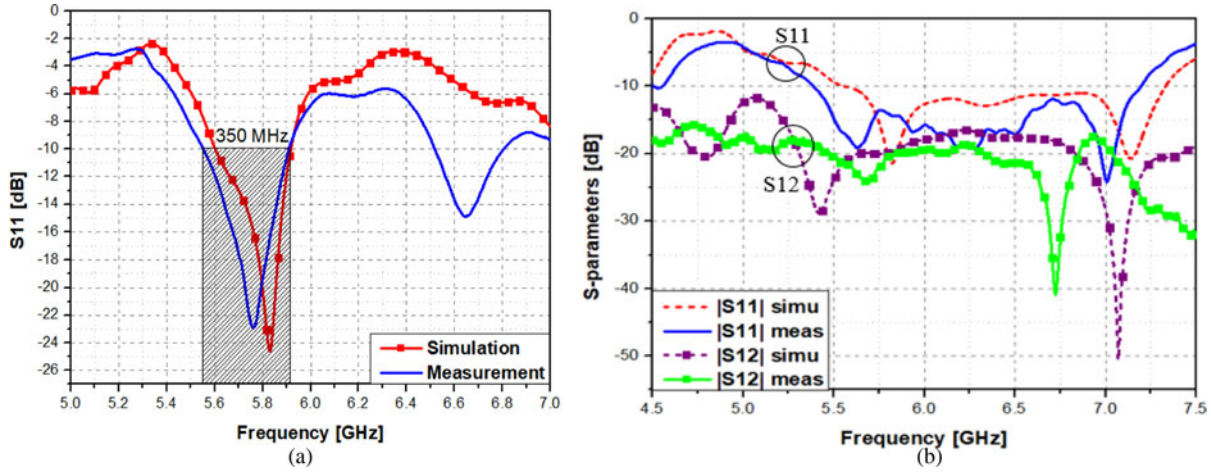


Fig. 17. Measurement results of the *S*-parameters: (a) single array antenna, (b) MIMO array antenna.

These show that using metamaterial structure to improve gain and bandwidth for antenna is the right method.

Figure 12 and Fig. 13 illustrate the simulated S-parameters, radiation pattern, and the normalized 5.8 GHz radiation pattern of the proposed antenna while Fig. 14 shows the gain and efficiency of the proposed antenna. From Fig. 12, we can see that the bandwidth of the proposed antenna is 1.8 GHz (at −10 dB) corresponding to the bandwidths in the percentage of approximately 31%. In addition, the isolation of the antenna is <−17 dB. Moreover, the gain of the antenna reaches 9.2 dBi while the efficiency is 73.14% (Fig. 14). Besides, another important parameter in the MIMO system to determine diversity performance is the envelope correlation coefficient (ECC). Here, ECC is defined as follows [23, 24]:

$$\boldsymbol{\rho_e} = \frac{|\boldsymbol{S}_{11}^{*}\boldsymbol{S}_{12} + \boldsymbol{S}_{21}^{*}\boldsymbol{S}_{22}|^2}{(1 - |\boldsymbol{S}_{11}|^2 - |\boldsymbol{S}_{21}|^2)(1 - |\boldsymbol{S}_{22}|^2 - |\boldsymbol{S}_{12}|^2)}, \tag{11}$$

and the ECC also can be calculated using the radiation pattern as [24]:

$$ECC = \rho_e = \frac{\left|\iint 4\pi[F_1(\theta, \varphi) \cdot F_2(\theta, \varphi)d\Omega\right|^2}{\iint 4\pi|F_1(\theta, \varphi)|^2 d\Omega \iint 4\pi|F_2(\theta, \varphi)|^2 d\Omega}. \tag{12}$$

https://doi.org/10.1017/S175907871900059X Published online by Cambridge University Press

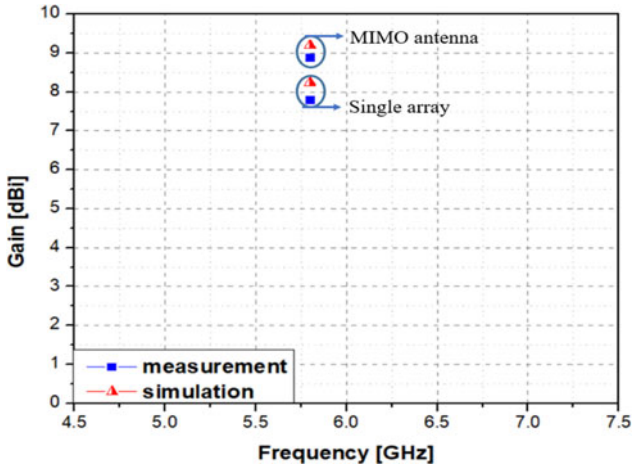


Fig. 18. The measurement results of gain for the proposed antennas.

Figure 15 shows the ECC of the proposed array antennas. From this figure, the proposed antenna has the simulated ECC lower than 0.02 for a wide frequency range. This is suitable for application with a minimum acceptable ECC of 0.5 [25].

Measurement results

To verify the performance of the proposed MIMO array antenna for WLAN application, the prototypes of the MIMO array antenna, as shown in Fig. 16, were fabricated on Roger4350B substrate material with a permittivity of 3.66 and the thickness of 1.524 mm. The dimensions of antennas are $70 \times 72 \times 3.048$ mm^3 and $137 \times 77 \times 3.048$ mm^3, respectively. Figure 17 shows the measurement results of *S*-parameters of the single array antenna and MIMO array antennas. It can be seen that the bandwidths of the single array antenna and MIMO array antenna are 350 and 1780 MHz, respectively. Besides, the mutual coupling of the antenna is lesser than −18 dB.

Figure 18 illustrates the measurement results of the gain of the proposed antenna. Here, the measurement results of gain of MIMO antenna and single array are 8.9 and 7.8 dBi while these values for simulation are 9.2 and 8.2 dBi, respectively. The results in this work have also been compared with the other works as shown in Table 4. Although the size of the proposed antenna is larger than the sizes in the references, the antennas in the references are single antenna instead of antenna array as the proposed paper. Therefore, this is acceptable. In addition, as can be seen that although the antenna in [26] has the large percentage of bandwidth (23.9%), the gain is only 5.5 dBi and the isolation of the antenna is only 17 dB. In other work [27], the gain and bandwidth percentage of the antennas are 7 dBi and 7.7%, respectively. Moreover, the isolation of the antenna in [27] is not good (14 dB). This also appears in [28] when the mutual coupling between antenna is very high (−12 dB). Besides, the bandwidth percentage and gain of this antenna are 8.8% and 4.3 dBi, respectively. Similarly, the antenna in [29] and [30], the isolation between antenna is only 15 dB, while the gains of antennas are very low (lesser than 2 dBi).

Meanwhile, the work in [31], the antenna includes two sets of two elements (1×2) and it is yielded at 5.8 GHz. Although the isolation of antenna is 34 dB, the gain and bandwidth percentage are low (7.8% and 5.3 dBi). In another aspect, the size of the

Table 4. The comparison between references and this work

References	[26]	[27]	[28]	[29]	[30]	[31]	My work
Frequency (GHz)	2.6	2.6	3.5	2.45	5.7	5.8	**5.8**
Bandwidth (%)	23.9	7.7	8.8	14.2	5.2	7.8	**30.6**
Isolation (dB)	17	14	12	15	15.4	34	**18**
Efficiency (%)	x	x	73	78	70	x	**73**
Gain (dBi)	5.5	7	4.3	1.26	1.41	5.3	**9.2**
Size (λ^3)	$0.68 \times 0.68 \times 0.0064$	$0.99 \times 0.99 \times 0.182$	$0.93 \times 0.47 \times 0.09$	$0.27 \times 0.147 \times 0.013$	$0.49 \times 0.49 \times 0.015$	$1.88 \times 0.54 \times 0.003$	**$2.64 \times 1.48 \times 0.058$**

https://doi.org/10.1017/S175907871900059X Published online by Cambridge University Press

antenna in [31] with two elements based on the substrate with higher dielectric constant (4.4) is smaller than our proposed antenna (with four elements and the dielectric constant of 3.66). We know that there is an inversely proportional relationship between the size of the antenna and the dielectric constant of the substrate [32]. In addition, the larger number of element also leads to increase the size of the antenna. Therefore, the size of the antenna in our paper is larger than the size in [31], this is understandable.

Conclusion

This paper has presented a MIMO array antenna for WLAN application in a compact size of $137 \times 77 \times 3.048$ mm^3. A metamaterial structure is proposed and it is applied to improve parameters of MIMO such as bandwidth, gain, and mutual coupling. Operating at 5.8 GHz, the proposed antenna gets wide bandwidth of 23.5%, high gain of 9.2 dBi, and good isolation of 18 dB. In addition, the antenna achieves a good radiation efficiency of 73%. The antenna prototypes were fabricated on Roger4350B and the antenna performances are verified through simulation and measurement. With the features of compact size, high gain and wide bandwidth, a planar structure and high isolation, the MIMO array antenna can be widely applied to WLAN applications.

Author ORCIDs. Nguyen Ngoc Lan, 0000-0001-8506-9979.

References

1. **Paulraj AJ, Gore DA, Nabar RU and Bölcskei H** (2004) An overview of MIMO communications – a key to gigabit wireless. *IEEE Proceedings* **92**, 198–217.
2. **Zheng L and Tse DNC** (2003) Diversity and multiplexing: a fundamental tradeoff in multiple-antenna channels. *IEEE Transactions on Information Theory* **49**, 1073–1096.
3. **Wang F, Duan Z, Li S, Wang Z and Gong Y** (2018) Compact UWB MIMO antenna with metamaterial-inspired isolator. *Progress in Electromagnetics Research c* **84**(April), 61–74.
4. **García-aguilar A, Inclán-alonso JM, Vigil-herrero L, Fernández-gonzález JM and Sierra-perez M** (2012) Low-profile dual circularly polarized antenna array for satellite communications in the x band. *IEEE Transactions on Antennas and Propagation* **60**, 2276–2284.
5. **Liu C, Member S, Guo Y, Member S and Xiao S** (2014) Capacitively loaded circularly polarized implantable patch. *IEEE Transactions on Antennas and Propagation* **62**, 2407–2417.
6. **Sourav Nandi AM** (2017) A compact dual-band MIMO slot antenna for WLAN applications. *IEEE Antennas and Wireless Propagation Letters* **16**, 2457–2460.
7. **Vaidya AR, Gupta RK and Mishra SK** (2014) Right-hand/left-hand circularly polarized high-gain antennas using partially reflective surfaces. *IEEE Antennas and Wireless Propagation Letters* **13**, 431–434.
8. **Ahdi Rezaeieh S, Antoniades MA and Abbosh AM** (2017) Gain enhancement of wideband metamaterial-loaded loop antenna with tightly coupled arc-shaped directors. *IEEE Transactions on Antennas and Propagation* **65**, 2090–2095.
9. **Gupta SD and Srivastava MC** (2012) Multilayer microstrip antenna quality factor optimization for bandwidth enhancement. *Journal of Engineering Science and Technology* **7**, 756–773.
10. **Guha D and Kumar C** (2014) Defected ground structure (DGS)-integrated rectangular microstrip patch for improved polarisation purity with wide impedance bandwidth. *IET Microwaves, Antennas & Propagation* **8**, 589–596.
11. **Gulam Nabi Alsath M, Kanagasabai M and Balasubramanian B** (2013) Implementation of slotted meander-line resonators for isolation enhancement in microstrip patch antenna arrays. *IEEE Antennas and Wireless Propagation Letters* **12**, 15–18.
12. **Exposito-dominguez G, Fernandez-gonzalez JM, Padilla P and Sierra-castaner M** (2012) Mutual coupling reduction using EBG in steering antennas. *IEEE Antennas and Wireless Propagation Letters* **11**, 1265–1268.
13. **Dadgarpour A, Sorkherizi MS and Kishk AA** (2016) Wideband low-loss magnetoelectric dipole antenna for 5 g wireless network with gain enhancement using meta lens and gap waveguide technology feeding. *IEEE Transactions on Antennas and Propagation* **64**, 5094–5101.
14. **Soltani S, Lotfi P and Murch RD** (2016) A port and frequency reconfigurable MIMO slot antenna for WLAN applications. *IEEE Transactions on Antennas and Propagation* **64**, 1209–1217.
15. **Xu HX, Wang GM and Qi MQ** (2013) Hilbert-shaped magnetic waveguided metamaterials for electromagnetic coupling reduction of microstrip antenna array. *IEEE Transactions on Magnetics* **49**, 1526–1529.
16. **Hwangbo S, Yang HY and Yoon YK** (2017) Mutual coupling reduction using micromachined complementary meander-line slots for a patch array antenna. *IEEE Antennas and Wireless Propagation Letters* **16**(C), 1667–1670.
17. **Chen H-T, O'Hara JF, Taylor AJ, Averitt RD, Highstrete C, Lee M and Padilla WJ** (2007) Complementary planar terahertz metamaterials. *Optics Express* **15**, 1084.
18. **Withawat Withayachumnankul DA and Fumeaux C** (2010) Compact electric-lc resonators for metamaterials. *Optics Express* **18**, 25912–25921.
19. **Chen X, Grzegorczyk TM, Wu BI, Pacheco J and Kong JA** (2004) Robust method to retrieve the constitutive effective parameters of metamaterials. *Physical Review E – Statistical Physics, Plasmas, Fluids, and Related Interdisciplinary Topics* **70**, 7.
20. **Rosu I.** Microstrip, stripline, and CPW design. Available at https://www.qsl.net/va3iul/Microstrip_Stripline_CPW_Design/Microstrip_Stripline_and_CPW_Design.pdf
21. **Ramesh Garg AI, Bhartia P and Bahl I** (2001) *Microstrip Antenna Design Handbook*. London: Artech House.
22. **Van Yem V and Lan NN** (2018) Gain and bandwidth enhancement of array antenna using novel metamaterial structure. *Journal of Communications* **13**, 101–107.
23. **Su SW** (2010) High-gain dual-loop antennas for MIMO access points in the 2.4/5.2/5.8 GHz bands. *IEEE Transactions on Antennas and Propagation* **58**, 2412–2419.
24. **Ibrahim AA, Abdalla MA and Hu Z** (2018) Compact ACS-fed CRLH MIMO antenna for wireless applications. *IET Microwaves, Antennas & Propagation* **12**, 1021–1025.
25. **Karaboikis MP, Papamichael VC, Tsachtsiris GF, Soras CF and Makios VT** (2008) Integrating compact printed antennas onto small diversity/MIMO terminals. *IEEE Transactions on Antennas and Propagation* **56**, 2067–2078.
26. **Ding K, Gao C, Qu D and Yin Q** (2017) Compact broadband MIMO antenna with parasitic. *IEEE Antennas and Wireless Propagation Letters* **16**, 2349–2353.
27. **Costa JR, Member S, Lima EB, Medeiros CR, Fernandes CA and Member S** (2011) Evaluation of a new wideband slot array for MIMO performance enhancement in indoor WLAN. *IEEE Transactions on Antennas and Propagation* **59**, 1200–1206.
28. **Jehangir SS and Sharawi MS** (2016) A single layer semi-ring slot yagi-like MIMO antenna system with high front-to-back ratio. *IEEE Transactions on Antennas and Propagation* **65**, 937–942.
29. **Yang L, Yan S and Li T** (2015) Compact printed four-element MIMO antenna system for LTE/ISM operations. *Progress in Electromagnetics Research Letters* **54**(July), 47–53.
30. **Pandit S, Mohan A and Ray P** (2018) A compact four-element MIMO antenna for WLAN applications. *Microwave and Optical Technology Letters* **60**, 289–295.
31. **Malviya L, Panigrahi RK and Kartikeyan MV** (2016) Circularly polarized 2×2 MIMO antenna for WLAN applications. *Progress in Electromagnetics Research C* **66**(July), 97–107.
32. **Yohei K, John F, Volakis L and Chen C-C** (2010) *Small Antennas: Miniaturization Techniques & Applications*. USA: Mc Graw Hill.

https://doi.org/10.1017/S175907871900059X Published online by Cambridge University Press



Nguyen Ngoc Lan received Master degree from the School of Electronics and Telecommunications, Hanoi University of Science and Technology, in 2014. From 2015 to 2018, she was a Ph.D. student at the School of Electronics and Telecommunications, Hanoi University of Science and Technology, Vietnam. Her research interests are microstrip antenna, mutual coupling, MIMO antennas, array antennas, reconfigurable antennas, polarization antennas, metamaterial, metasurface.



Vu Van Yem received Ph.D. degree from the Department of Electronics and Communications, TELECOM ParisTech, France, in 2005. From 2006 to 2007, he was a postdoctoral researcher at the Department of Hyper-Frequency, the Institute of Electronics and Microelectronics and Nano technology (IEMN), France. He has been qualified as an associate professor since 2009. He is the head of president's office as well as head of RF & Microwave Lab, Hanoi University of Science and Technology, Vietnam. His research interests are microwave engineering, antenna, chaos-based digital communications as well as advanced wireless communication and localization.

https://doi.org/10.1017/S175907871900059X Published online by Cambridge University Press