Gain and Bandwidth Enhancement of Array Antenna Using a Novel Metamaterial Structure

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Abstract—Today, wireless communication systems always require an antenna with broadband capability, high gain and efficiency, which are especially important in satellite communications. With advantages, such as high gain and wide bandwidth, an array antenna is often used in many different applications. A compact array antenna of 4 x 4 elements using a novel metamaterial structure is proposed in this paper. The array antenna consists of 16 patch elements and a novel metamaterial structure. By using the metamaterial structure on the ground plane, the bandwidth and gain of the array antenna are significantly improved. The array antenna was constructed on Roger4350B with a thickness of 1.524 mm, ε_r = 3.66 and tanδ = 0.0037 over the frequency range from 7.9 to 8.4 GHz. The antenna displays a large bandwidth of approximately 13.5%, a high gain over 11.2 dBi and an efficiency of 87%. The experimental results were compared to those obtained in a simulation to verify the performance of the proposed array antenna.

Index Terms—Array antenna, microstrip antenna, metamaterial antenna, metamaterial reflective surface

I. Introduction

In recent years, wireless communication has rapidly developed with many different services. With advantages such as large bandwidth and coverage, satellite communication has been widely used in both commercial and military applications. In these systems, the antenna is an indispensable component whose quality directly affects the transceiving progress. In addition, modern systems always require a small device size. The introduction of microstrip technology has met part of the aforementioned requirements. With advantages such as small size, low weight, easy fabrication and low production cost, microstrip antennas have increasingly widespread applications. Besides the as-mentioned advantages, they still have some limitations such as narrow bandwidth, low gain and low efficiency, which bring many challenges for antenna designers.

Currently, different methods have been adopted to improve the gain, bandwidth and efficiency of antennas, for example, electromagnetic band gap (EBG) [1], two dielectric superstrates [2], hybrid high impedance surface (HIS) [3], defected ground structure (DGS) [4], artificial magnetic conductor (AMC) [5] and metamaterial (MTM) [6], [7]. One of the most attractive methods used to improve an antenna's parameters is using a metamaterial structure. Metamaterials are attracting a lot attention from researchers in different fields, such as optics, microwave and so on. Metamaterials are also known as left-hand materials. Each type of metamaterial has its own characteristics [8] and therefore, they have been studied in many different fields [9], [10]. By using a metamaterial structure, some parameters of the antenna can be improved, for example, the bandwidth [11], gain [12], efficiency [13] and specific absorption rate (SAR) [14]. Therefore, the use of metamaterial structures is currently a new trend in the field of antennas and microwaves.

Besides, an array antenna has several advantages including broadband capability, high gain, and directivity. Therefore, using an array antenna is also one of the methods used to improve the bandwidth and gain [15]. However, they have some limitations. In [15], although the antenna was designed at a central frequency of 11 GHz, the antenna efficiency was only 65%. Similarly, in [16], an antenna including 16 elements was designed at a central frequency of 11 GHz, but the gain of the antenna was only 8.1 dBi. In another study, an antenna including 16 elements was designed at a central frequency of 11.5 GHz, but the bandwidth percentage of the antenna was only 6% [17]. It is clear that an improvement in the antenna parameters is still necessary.

Another important aspect of antenna design is antenna miniaturization. The proposed solutions include dielectric loading [18], metamaterial [19], the loop loading technique [20], fractal geometry [21] and wire loading [22]. The aim was to decrease the number of elements and dimensions of the antenna, while maintaining high gain, large bandwidth, and high efficiency. This paper proposes a compact 4 x 4 array antenna using a new metamaterial structure. The proposed array antenna was designed, simulated, and fabricated on a Roger4350B substrate. By using the proposed metamaterial structure on the ground plane, not only the antenna bandwidth was improved, but also the gain of the antenna was increased. In addition, the size of the proposed array antenna was also reduced.

II. Principle of the Bandwidth and Gain Enhancement Using a Metamaterial Structure

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A. Principle of the bandwidth enhancement using a metamaterial structure

We know that a zeroth-order resonace antenna has the advantage of miniaturization because the propagation constant is zero. The frequency and bandwidth of the antenna can be calculated as follows:

$$\omega_{ZOR} = \omega_E = 1/\sqrt{L_L C_R} \tag{1}$$

$$BW_{ZOR} = G\sqrt{\frac{L_L}{C_R}} \tag{2}$$

However, its narrow bandwidth is one of the antenna's disadvantages [23]. From the above equations, we can see that the bandwidth of the antenna depends on G, L_L, and C_R. To enhance the bandwidth of the antenna, we can increase the value of L_L and G, or decrease C_R. However, an increase in the L_L value is limited by the resonant frequency and Chu criterion [24]. In addition, increasing the bandwidth leads to a decrease in the efficiency of the antenna. Therefore, to obtain a highly efficient antenna while retaining an enhanced bandwidth, we can merge the consecutive cavity resonators together [23]. Herein, we need to distinguish the difference in the bandwidth enhancement observed for an antenna and multi-band antenna upon merging the cavity resonators. To improve the bandwidth of the antenna, we created consecutive cavity resonators while in the multi-band antenna, the cavity resonators were not consecutive. This interruption depends on the distance between the frequencies used to design the antenna.

If we consider a rectangular cavity, then the wavenumber is given by equation (3) [25].

$$k_{mnl} = \sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \tag{3}$$

where *m*, *n*, and *l* are the values of the standing wave in the of *x*-, *y*-, and *z-axes*, respectively. The resonant frequency can then be calculated as follows:

$$f_{mnl} = \frac{ck_{mnl}}{2\pi\sqrt{\mu_r\varepsilon_r}} = \frac{c}{2\pi\sqrt{\mu_r\varepsilon_r}}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2 + \left(\frac{l\pi}{d}\right)^2} \tag{4}$$

B. Principle of antenna gain enhancement using a metamaterial structure

We know that using a metamaterial structure on the ground plane causes disorder in the current distribution. This leads to the fact that there are interferences between the waves and then, the current re-distribution is implemented. In this part, we will discuss in detail the current re-distribution and how to increase the antenna gain using a metamaterial structure.

According to [26], the interference is a phenomenon of overlapping between the waves. To display this interference, the waves must be coherent to each other. This is satisfied because the waves in the antenna have the same source and frequency. If we consider two coherent waves with the same frequency, amplitude, and polarization but a difference in phase, by assuming the propagation is in the z-direction, then interference occurs. Subsequently, the total field can be calculated as follows [27]:

$$E_1 = E_0 e^{i(kx-\omega t-\varphi_1)}\hat{Z} \tag{5}$$

$$E_2 = E_0 e^{i(kx-\omega t-\varphi_2)}\hat{Z} \tag{6}$$

$$E_t = E_1 + E_2$$

$$= 2E_0\left[\cos\left(kx - \omega t - \frac{\varphi_1+\varphi_2}{2}\right)\cos\left(\frac{\varphi_1-\varphi_2}{2}\right) + i\sin\left(kx - \omega t - \frac{\varphi_1+\varphi_2}{2}\right)\cos\left(\frac{\varphi_1-\varphi_2}{2}\right)\right] \tag{7}$$

$$= 2E_0\cos\left(\frac{\varphi_1-\varphi_2}{2}\right)e^{i\left(kx-\omega t-\frac{\varphi_1+\varphi_2}{2}\right)}\hat{Z} \tag{8}$$

where E_0 is the amplitude and φ_1 and φ_2 are the phases of the first wave and second wave, respectively. The Poynting vector and magnetic (B) are given by:

$$B_t = 2E_0\cos\left(\frac{\varphi_1-\varphi_2}{2}\right)e^{i\left(kx-\omega t-\frac{\varphi_1+\varphi_2}{2}\right)}\hat{y} \tag{9}$$

$$S_t = \vec{E}\times\vec{H} = \frac{1}{\mu}\overrightarrow{B_t}\times\vec{H} = \frac{1}{\mu}4E_0^2 cos^2\left(\frac{\varphi_1-\varphi_2}{2}\right)e^{2i\left(kx-\omega t-\frac{(\varphi_1+\varphi_2)}{2}\right)}\hat{x} \tag{10}$$

From equation (10), we can see that the energy flow is at a maximum when there is no phase difference between the waves. When the phase difference is an odd multiple of π (..., -π, π, 3π,...), the energy flow in the antenna cannot move along the direction of propagation. Therefore, to enhance the gain of the antenna, we need to re-distribute the current so that more of the energy flows with no phase difference. Therefore, the amplitude of the total wave is the sum of the component amplitudes.

III. The Proposed Array Antenna

A. The proposed metamaterial structure

The model of the proposed metamaterial structure and its equivalent circuit are illustrated in Fig. 1. The structure is planar and consists of a nest of rectangles. The proposed structure has a small size (27 x 27 mm). In this structure, the gaps between the two microstrip lines create equivalent capacitances, while the inductances are created by the microstrip lines.

We know that the distribution of the field between the patch and ground will decide the radiation of the microstrip antenna. In the other words, the radiation can be explained using the surface current distribution [28]. This is normally a uniform distribution, however, when a metamaterial structure is used, some of the characteristics of the transmission line (such as electrical length and slow wave factor) are changed upon adding inductance or capacitance. In addition, there is a current re-distribution in the antenna when a metamaterial structure is used. This opens up the opportunity to improve the gain and directivity of the antenna. Based on the above principles of gain and bandwidth enhancement, the design of an

antenna with a large bandwidth and high gain is possible by controlling the phase shift between the currents and merging the cavity resonators.

According to [8], a metamaterial is a a type of material that has simultaneously negative permittivity and permeability. To confirm the proposed structure is a metamaterial structure, this paper established a simulation consisting a microstrip line of 50 Ohm and the proposed structure on the ground plane. The parameters of the proposed structure used for the simulation are shown in Table I. The structure is proposed for the frequency range of 7.9 – 8.4 GHz. The material chosen for the substrate is Roger4350B with a thickness of 1.524 mm, ε_r = 3.66 and tanδ = 0.0037. The ε and μ values were determined from the S-parameters using the equations in [29], [30]. Fig. 2 illustrates the simulation results with the S-parameters, ε and μ values.

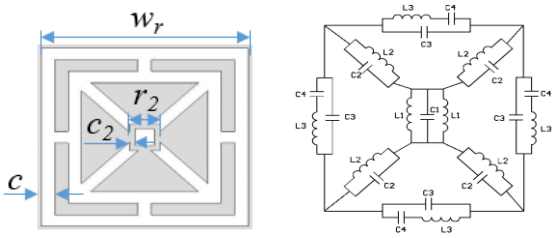

Fig. 1. The model of the proposed structure and their equivalent circuit: (a) Metamaterial structure and (b) its equivalent circuit.

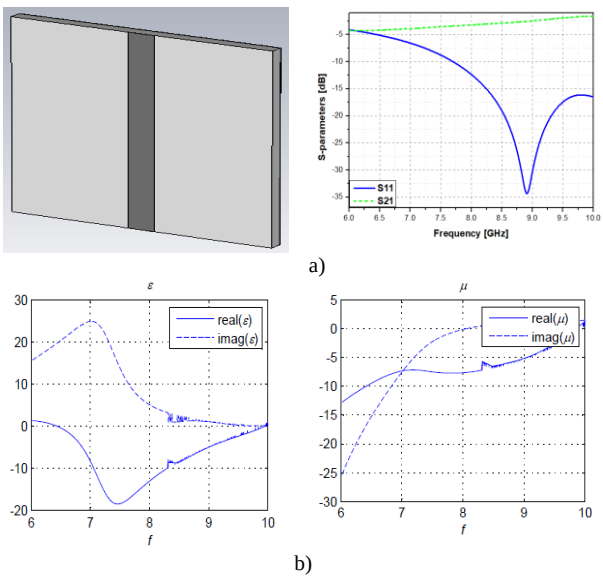

Fig. 2. (a) The S-parameters used for the simulation set-up and (b) the simulation results.

From Fig. 2, we can see that the ε and μ values are simultaneously negative in the frequency range of 7 – 9 GHz. This shows that the proposed structure is a metamaterial.

TABLE I: THE PARAMETERS USED FOR THE VERIFICATION OF THE PROPOSED STRUCTURE (UNIT: MM).

Parameter	w_r	c	c_2	r_2
Value	12	2	1.5	3

B. Design of the array antenna

The models of an element and the array antenna are shown in Fig. 3. The array antenna consists of 16 patch elements with 15 T-junction power dividers on the radiation layer and the novel metamaterial structure on the ground plane. The distance between the elements was approximately 20 mm. The antenna was designed for the frequency range from 7.9 to 8.4 GHz and the size of the substrate was 115 x 118 mm. The proposed antenna array was constructed on a Roger4350 substrate with a thickness of 1.524 mm, ε_r = 3.66 and tanδ = 0.0037. Using the formulas in [31], we can calculate the size of the element. Table II shows the parameters of the element.

Here, the impedance of the microstrip line was calculated as follows [32]:

$$\text{If } w/h < 1 \qquad Z_0 = \frac{60}{\sqrt{\varepsilon_{eff}}} \cdot ln\left(\frac{8h}{w} + \frac{w}{4h}\right) \tag{11}$$

$$\text{If } w/h > \qquad Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}}} \cdot \frac{1}{\left(\frac{w}{h}+1.393+0.677ln\left(\frac{w}{h}+1.444\right)\right)} \tag{12}$$

where ε_{eff} is the effective dielectric constant. In this case, because the impedance of the microstrip line was 50 Ohm, the width of the microstrip line was approximately 3.45 mm.

In addition, quarter-wave transformers were used to match the impedance to the power dividers. The impedance of the quarter-wave transformers is given by:

$$Z_T = \sqrt{Z_0 Z_{in}} \tag{13}$$

where Z_{in} is the input impedance of the line and Z_0 is the characteristic impedance.

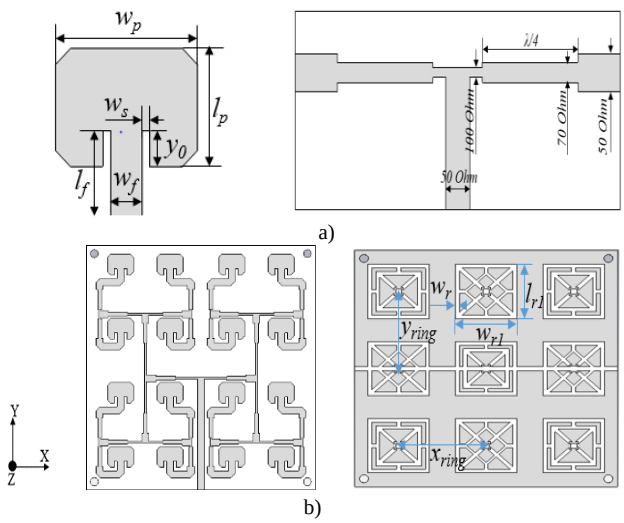

Fig. 3. The model of the element, proposed array antenna and power divider: (a), top-view and back-view (b)

TABLE II: THE PARAMETERS OF AN ELEMENT IN THE ARRAY (UNIT: MM).

Parameter	w_f	l_f	w_s	l_p	w_p	y_0
Value	3.45	8	1.5	10	13	3

To enhance the antenna bandwidth, the metamaterial structure was used on the ground plane. The proposed

model and its equivalent circuit are shown in Fig. 1. The capacity and inductor are given by [33]:

$$C_i = \varepsilon_r \varepsilon_0 \times (A/h) \tag{14}$$

$$L(nH/mm) = 0.2\left[ln\left(\frac{l}{w+t}\right) + 1.193 + 0.2235\frac{w+t}{l}\right] \tag{15}$$

where ε_r is the dielectric constant of substrate, ε_0 is the permittivity of space, A is the area of the plate (L x W), h is the thickness of the substrate, w and l are the width and length of the ribbon, respectively and t is the metamaterials thickness.

When the elements are shunt:

$$C_{total} = \sum_{i=1}^{n} C_i \tag{16}$$

$$L_{total} = \frac{1}{L_1} + \frac{1}{L_2} + \cdots \frac{1}{L_n} \tag{17}$$

When the elements are in series:

$$C_{total} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots \frac{1}{C_n} \tag{18}$$

$$L_{total} = \sum_{i=1}^{n} L_i \tag{19}$$

Then, the resonant frequency is given by:

$$f_{re} = \frac{1}{2\pi f\sqrt{L_{total}C_{total}}} \tag{20}$$

By using the formulas shown above, we can calculate the size of the metamaterial structure and the resonant frequency of the antenna. Here, the size of each unit structure was 27 x 27 mm, while the distance between the unit structures was approximately 38 mm and 38.5 mm, respectively. The parameters of the ground plane are shown in Table III.

TABLE III: SOME PARAMETERS OF THE METAMATERIAL STRUCTURE (UNIT: MM).

Parameter	*wr*	*lr1*	*wr1*	*y_ring*	*x_ring*
Value	3.5	27	27	38.5	38

It can be observed from equation (20) that with a determinant frequency of f, the product of L and C is a constant. However, each specific value of L and C can change. This explains why at each identified resonant frequency with the same model and the same structure of antenna, we can obtain many different results for the parameters of the antenna. As a result, the resonant frequency does not depend on the number of cells on the ground plane. To reach the better parameters, we need to select the right number of cells. However, we know that the bandwidth and gain of an antenna do not increase linearly with the number of cells on the ground plane. Moreover, when the number of cells increases, the complexity of the antenna structure also increases, which leads to an increase in the time taken for one task. Therefore, the number of cells on the ground plane should be selected to achieve good results and to reduce the complexity. For this reason, the selected number of cells was 9 in this paper.

IV. SIMULATION AND MEASUREMENT RESULTS

A. Simulation results

First of all, to illustrate the effect of the proposed structure on the parameters of the antenna, this paper simulated an antenna without the metamaterial structure. Fig. 4 and Fig. 5 show the difference between the bandwidth and radiation pattern of the antenna with and without the metamaterial, respectively.

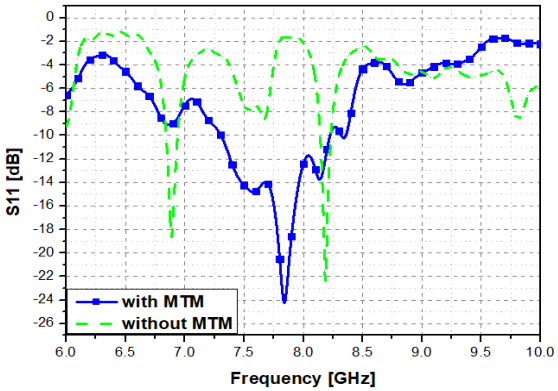

Fig. 4. The difference in the bandwidth of the antenna with and without the metamaterial, respectively.

From Fig. 4, we can see that there is a significant difference in the bandwidth of the antenna with and without the metamaterial. While the bandwidth of the antenna with the metamaterial is 1.1 GHz (approximately 13.5%), this value without the metamaterial is only about 100 MHz. It is clear that by using the metamaterial structure on the ground plane, a large number of consecutive cavity resonators were created. As a result, the bandwidth of the antenna was improved. Using this method, we can enhance the bandwidth for an antenna while maintaining high efficiency. Moreover, using a metamaterial also creates parasitic capacitance and inductance, which is attributed to a change in the electrical length with no change in the physical length. Subsequently, the size of the antenna is reduced.

As shown in Fig. 5, it is clear that there was a significant difference between the radiation patterns when the array antenna is prepared with and without the metamaterial. Without the metamaterial, the directivity of the antenna is very low (Fig. 5a). The magnitude of the main lobe is only 4.21. In addition, the side lobe level is quite high. As a result, the gain of the antenna is low. In this case, the gain of the antenna was only over 6 dBi. Here, the current distribution in the antenna is almost uniform. Therefore, the interference between the waves is low. The energy flows cannot concentrate at a location where there is constructive interference, which leads to the low gain and directivity of the antenna. However, when the metamaterial structure is used on the ground plane, there is a current re-distribution in the antenna and an interference between the waves occurs. By adjusting

the current distribution such that there is more energy flow in the constructive interference and less energy flow in the deconstructive interference, then an antenna with high directivity and gain is possible This has been applied to the antenna using the proposed metamaterial structure. Fig. 5b illustrates the radiation pattern of the antenna with a metamaterial structure. From Fig. 5b, we can see that the directivity of the antenna is quite high, which is shown by the main lobe magnitude of 13.3 and an angular width (3dB) of 23.4°. Moreover, the side lobe level of the antenna is quite low (-6 dB). Besides, the efficiency of the antenna with the proposed metamaterial structure reached over 87%, while the value without the metamaterial was only 73%. It is clear that using the metamaterial structure not only improved the bandwidth and gain of the antenna, but also it reduced the size of theantenna.

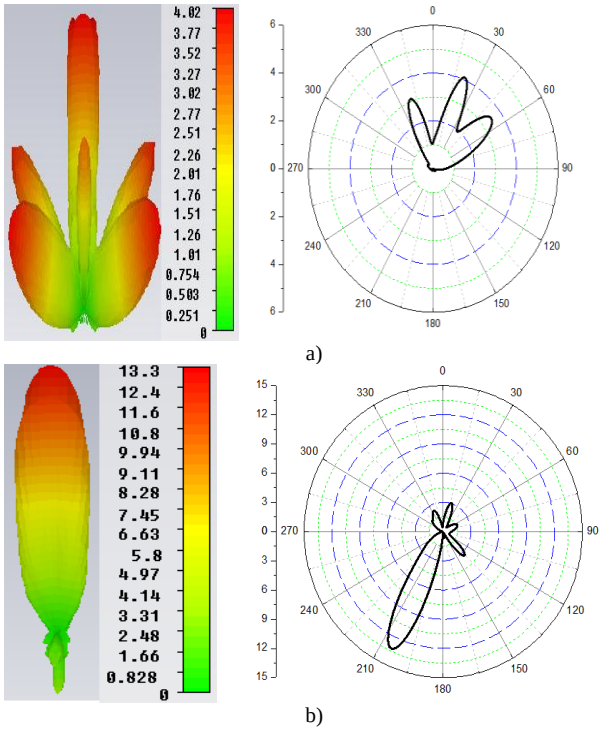

Fig. 5. The difference in the radiation pattern of the antenna (a) without and (b) with the metamaterial, respectively.

Fig. 6 shows the efficiency and gain of the antenna with the proposed metamaterial structure.

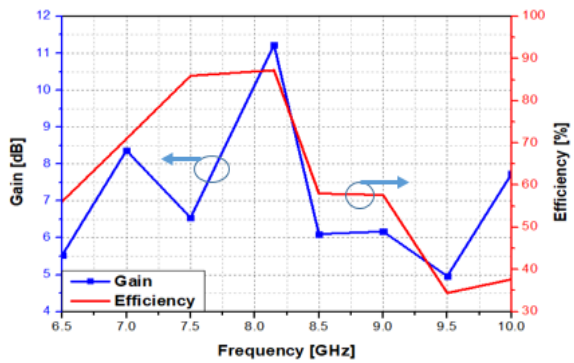

Fig. 6. The gain and efficiency of the antenna with the proposed metamaterial structure.

In Fig. 6, we can see that the gain of the antenna is over 11.2 dBi and the efficiency is 87%. The antenna reaches the highest value for both the efficiency and gain at a central frequency of 8.15 GHz. This shows the impedance matching for the antenna is very good.

Fig. 7 illustrates the radiation pattern of the proposed antenna in xz and yz plane.

In here, the directivity of the main lobe in yz plane is 205° while this value in xz plane is 24°.

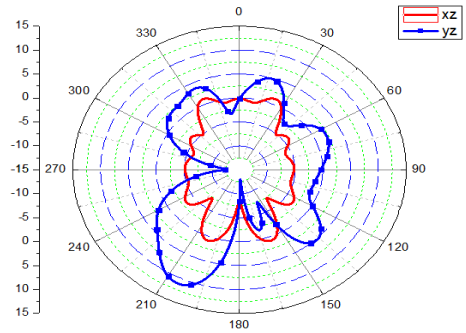

Fig. 7: The radiation pattern in xz and yz plane

B. *Measurement results*

Fig. 7 illustrates the fabricated antenna based on a Roger4350B substrate with a thickness of 1.524 mm, dielectric constant of 3.66 and tanδ = 0.0037. The size of the antenna is 115 x 118 mm.

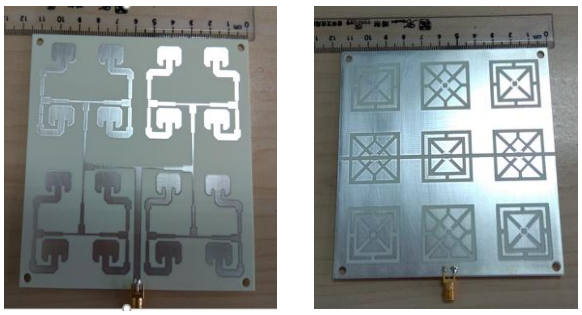

Fig. 7. The fabricated antenna based on a Roger4350B substrate: (a) Top-view and (b) back-view.

Fig. 8 shows the results of the antenna reflection coefficient measurements, which were compared to the simulation results. We can see that although there is a difference between the simulation and experimental results, the operating frequency range of the antenna was still guaranteed. Therefore, these results are acceptable. In addition, the impedance bandwidth of the antenna was greater than 1.2 GHz and the corresponding bandwidth percentage was approximately 15%. Moreover, the return loss of the antenna was very small, which shows the impedance matching for antenna was very good.

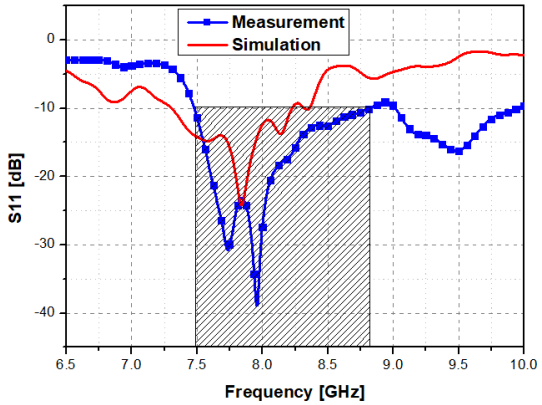

Fig. 8. The results for antenna reflection coefficient measurements.

When compare to some of the previously reported results, we can see as the following trends. As in [34], although the antenna including 16 elements was designed at a central frequency of 10.5 GHz, the gain of the antenna was only 10.3 dBi. Similarly, in [35], the 4 x 4 array antenna was designed at a central frequency of 10 GHz, but the bandwidth percentage was only 5%. With the above parameters, the array antennas were not sufficient enough for applications in the X-band region. In another research study, the efficiency of the antenna was only 67% when the frequency of the antenna was 35 GHz [36].

V. Conclusions

In this paper, a new metamaterial structure has been proposed and successfully applied to improve the parameters of a compact array antenna of 4 x 4 elements. The array antenna consists of 16 patch elements on the radiation layer and a novel metamaterial structure on the ground plane. The array antenna was constructed on a Roger4350B substrate with a thickness of 1.524 mm, ε_r = 3.66 and tanδ = 0.0037 for the frequency range from 7.9 to 8.4 GHz used for satellite applications. The antenna achieves a large bandwidth is approximately 13.5%, a high gain over 11.2 dBi, an efficiency of 87% and a compact size of 115 x 118 mm. By using the new metamaterial structure, not only the bandwidth of the antenna is improved, but also the gain is enhanced. In addition, the size of the array antenna is also reduced by enhancing the slow-wave factor. Moreover, the paper also analyzes the principles for the improvement of the bandwidth and gain of the antenna using the metamaterial structure.

With the parameters achieved as aforementioned, the proposed array antenna can meet the requirements of satellite applications in the X-band region. Moreover, with advantages such as low fabrication cost, low weight, small size and improved parameters, the proposed array antenna and its principle can be widely applied in practice for other applications.

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