Gain and Bandwidth Enhacement of Array Antenna Using Novel Metamaterial Structure

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Abstract**—**Today, wireless communication systems always require antenna with broadband capability, high gain and efficiency which are especially important in satellite communications. With advantages such as high gain and wide bandwidth, array antenna is much more used for different applications. A compact array antenna of 4x4 elements using novel metamaterial structure is proposed in this paper. The array antenna consists of 16 patch elements and a novel metamaterial structure. By using metamaterial structure on the ground plane, bandwidth and gain of array antenna are significantly improved. The array antenna is designed on Roger4350B with thickness of 1.524 mm, ε_r = 3.66, tanδ = 0.0037 for frequency range from 7.9 to 8.4GHz. The antenna gets a large bandwidth approximately 13.5%, a high gain over 11.2dBi and an efficiency of 87%. The measurement results are compared to simulation ones 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 been developing rapidly with many different services. With advantages such as large bandwidth and coverage, satellite communication is widely used in both commercial and military applications. In these systems, antenna is an indispensable component whose quality affects directly to transceiving progress. In addition, modern systems always require small device size. The introduction of microstrip technology has met a part of the aforementioned requirements. With advantages such as small size, lightweight, easy fabrication and low production cost, microstrip antennas have increasingly widespread applications. Besides the mentioned advantages, they still have some limitations, for example: narrow bandwidth, low gain and low efficiency which bring many challenges for antenna designers.

Currently, different methods have been adopted to improve 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], metamaterial (MTM) [6], [7]. One of the most attractive method to improve antenna parameters is using the metamaterial structure. Metamaterials are getting much attention of researchers from different fields such as optic, microwave and so on. Metamaterial is also known as Left Hand Material (LHM). Each metamaterial type has its own characteristics [8] and therefore, it is being studied for many different fields [9], [10]. By using metamaterial structure, some parameters of antennas can be improved, for example: bandwidth [11], gain [12], efficiency [13], Specific Absorption Rate (SAR) [14] and so on. Therefore, using of metamaterial structures is currently a new trend in the antenna and microwave field.

Besides, the array antenna has good points: broadband, high gain and directivity. Therefore, using array antennas is also one of the ways to improve bandwidth and gain [15]. However, there are some limitations in some published papers. In [15], although the antenna is designed at the central frequency 11 GHz, the antenna efficiency is only 65%. Similarly, in [16], the antenna including 16 elements is designed at frequency of 11GHz, but the gain of antenna is only 8.1 dBi. In another study, the antenna including 16 elements is designed at frequency 11.5 GHz, but the bandwidth percentage of antenna is only 6% [17]. It is clear that the improvement of antenna parameters is still neccessary.

Another important aspect of the antenna design is antenna miniaturization. The proposed solutions include dielectric loading [18], metamaterial [19], loop loading technique [20], fractal geometry [21], wire loading [22]. The aim is to descrease the number of elements and dimensions of antenna while maintaining the high gain, large bandwidth and high efficiency. This paper proposes a compact 4x4 array antenna using a new metamaterial structure. The proposed array antenna is designed, simulated and fabricated on Roger4350B substrate. By using the proposed metamaterial structure on the ground plane, not only the antenna bandwidth is improved, but also the gain of antenna is increased. In addition, the size of the proposed array antenna is also reduced.

II. PRINCIPLE OF THE BANDWIDTH AND GAIN ENHANCEMENT BY USING METAMATERIAL STRUCTURE

A. Principle of the Bandwidth Enhancement by Using Metamaterial Structure

We know that Zeroth-Order Resonace (ZOR) antenna has advantage, that is miniaturization because the

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propagation constant is zero. Then, the frequency and bandwidth of antenna can be calculated as follows, respectively:

$$\omega_{ZOR} = \omega_E = 1/\sqrt{L_L C_R} \quad (1)$$

$$BW_{ZOR} = G\sqrt{\frac{L_L}{C_R}} \quad (2)$$

However, the narrow bandwidth is its one of disadvantages [23]. From the above equations, we can see that the bandwidth of antenna depends on G, L_L and C_R. To enhance bandwidth for antenna, we can increase the value of L_L and G, or decrease C_R. However, the increase of L_L value is limitted by Chu criterion [24]. In addition, in this case, increasing the bandwidth leads to decreasing the efficiency of antenna. Therefore, to reach the high efficiency for antenna while the bandwidth is still enhanced, we can merge consecutive cavity resonators together. This is not only to enhance the bandwidth of antenna, but also it helps to get high efficiency. This is illustrated in [23]. Here, we need to distinguish about the difference between merging cavity resonators in the bandwidth enhancement for antenna and multi-band antenna. To improve bandwidth of antenna, we create consecutive cavity resonators while with multi-band antenna, the cavity resonators are not consecutive. This interruption depends on the distance between the frequencies that you want to design for antenna.

Now, we consider a rectangular cavity. Then, the wave number is given by [25]

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

in which, *m*, *n*, *l* are the values of standing wave in axises of *x*, *y*, *z*, respectively. Then, the resonant frequency can calculated as follows:

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

B. Principle of Antenna Gain Enhancement by Using Metamaterial Structure

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

According to [26], the interference is a phenomenon of overlaps between waves. To appear the interference, the waves must be coherent each other. This is satisfied because waves in antenna are same source and frequency. Let consider two coherent waves with the same frequency, amplitude and polarization but there is a difference in phase. Assuming that the propagation is in the z direction, then, the interference appears, and the total field can be calculated as follows [27]:

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

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

$$E_t = E_1 + E_2$$

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

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

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

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

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

From equations (10), we can see that the energy flow is maximum when there is no phase difference between waves. When the phase difference is the odd multiple of π (..., -π, π, 3π,...), the energy flow in antenna can not propagate along the propagation direction. Therefore, to enhance gain for antenna, we need to re-distribute current such that more and more the energy flows at place that the phase difference are zero. Then, the amplitude of the total wave is the sum of component amplitudes.

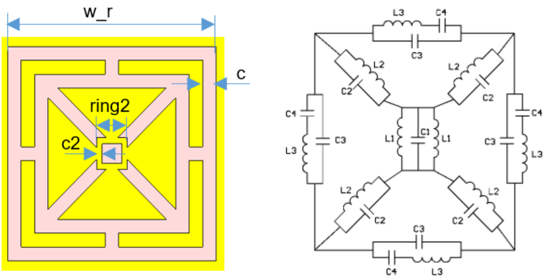
III. The Proposed Array Antenna

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 small size (27 x 27 mm). In this structure, the gaps between two microstrip lines creat equivalent capacitances while the inductances are created by microstrip lines.

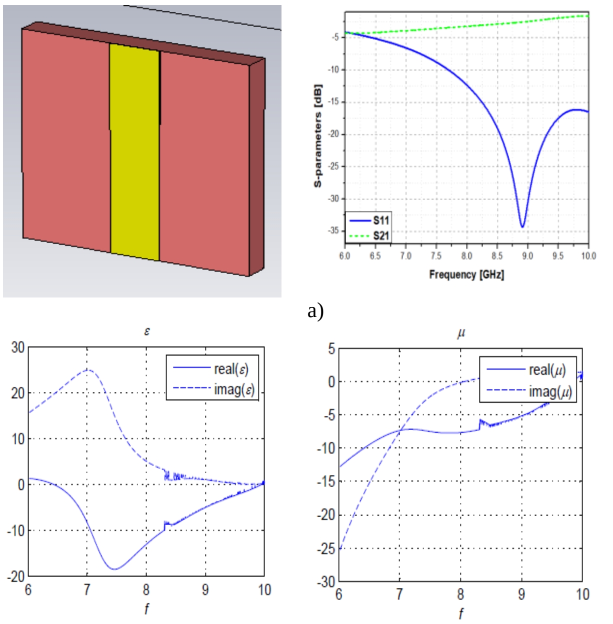
We know that the distribution of field between the patch and ground will decide the radiation of a microstrip antenna. In the other words, the radiation can be explain through the surface current distribution [28]. Therefore, normally, this is uniform distribution. However, when metamaterial structure is used, some characteristics of transmission line such as electrical length, slow wave factor… are changed through adding inductances or capacitances. In addition, there is a current re-distribution in antenna when metamaterial structure is used. And this opens an opportunity in gain and directivity improvement for antenna. Based on the above principles of the gain and bandwidth enhancement, the design of antenna with large bandwidth and high gain are possible by controlling the phase shift between the currents and the merging between the cavity resonators.

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



a) b)

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



a)

b)

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

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

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

Parameter	*w_r*	*c*	*c2*	*ring2*
Value	12	2	1.5	3

B. *Design of Array Antenna*

The models of an element and 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 a novel metamaterial structure on ground plane. The distance between elements is approximately 20 mm. The antenna is designed for frequency range from 7.9 to 8.4 GHz. The size of substrate is 115 x 118 mm. The proposed antenna array is designed on Roger4350 substrate with thickness of 1.524 mm, ε_r = 3.66 and tanδ = 0.0037. By using formulars in [31], we can calculate the size of the element. Table II shows the parameters of an element.

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

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

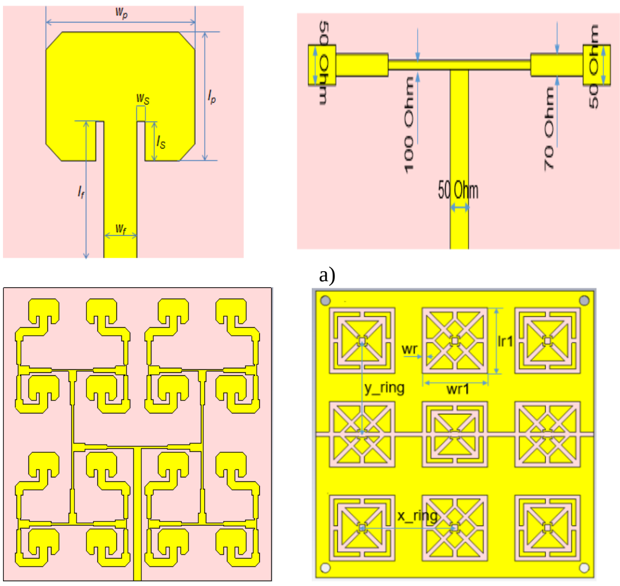
If w/h > $$Z_0 = \frac{120\pi}{\sqrt{\varepsilon_{eff}}} \cdot \frac{1}{\left(\frac{w}{h}+1.393+0.677ln\left(\frac{w}{h}+1.444\right)\right)} \quad (12)$$

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

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

$$Z_T = \sqrt{Z_0 Z_{in}} \quad (13)$$

with Z_{in} is input impedance of line, Z_0 is characteristic impedance.



a)

b)

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

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

Parameter	w_f	l_f	w_S	l_p	w_p	l_s
Value	3.45	8	1.5	10	13	3

To enhance antenna bandwidth, this paper uses metamaterial structure on ground plane. The proposed model and its equivalent circuit are shown in Fig. 1. Here, the capacity and inductor are given [33]:

$$C_i = \varepsilon_r \varepsilon_0 \times (A/h) \quad (14)$$

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

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

When the elements are shunt:

$$C_{total} = \sum_{i=1}^{n} C_i \quad (16)$$

$$L_{total} = \frac{1}{L_1} + \frac{1}{L_2} + \cdots \frac{1}{L_n} \quad (17)$$

And the elements are series:

$$C_{total} = \frac{1}{C_1} + \frac{1}{C_2} + \cdots \frac{1}{C_n} \quad (18)$$

$$L_{total} = \sum_{i=1}^{n} L_i \quad (19)$$

Then, the resonant frequency is given by:

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

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

TABLE III: SOME PARAMETERS OF 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. Therefore, this explains why at each identified resonant frequency with the same model and the same structure of antenna, we can obtain many different results about the parameters of antenna. As a result, the resonant frequency does not depend on the number of cells on 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 antenna do not increase linearly with number of cells on ground plane. Moreover, when the number of cell increases, the complexity of antenna structure is also increasing and this leads to the increase of time for one task. Therefore, the number of cell on ground plane should be selected to achieve good result and to reduce the complexity. For this reason, the selected number of cell is 9 in this paper.

IV. SIMULATION AND MEASUREMENT RESULTS

A. Simulation Results

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

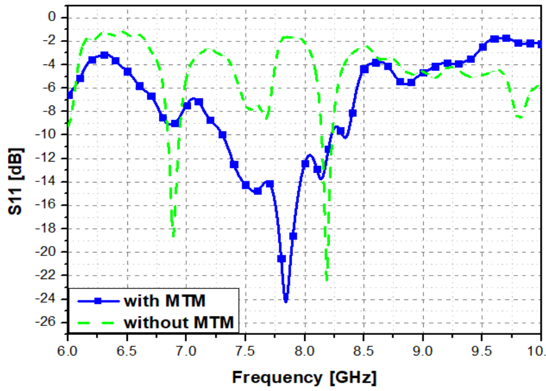


Fig. 4. The difference in bandwidth of antenna with and without metamaterial

From Fig. 4, we can see that there is a significant difference in the bandwidth of antenna with and without metamaterial. While the bandwidth of antenna with metamaterial is 1.1 GHz (approximately 13.5%), this value without metamaterial is only about 100 MHz. It is clear that through using metamaterial structure on ground plane, a lot of consecutive cavity resonators are created. As a result, the bandwidth of antenna is improved. By this method, we can enhance the bandwidth for antenna while keeping high efficiency. Moreover, using metamaterial also creates parasitic capacitances and inductances, this leads to the fact that there is a change in electrical length while there is no change in physical length. Then, the size of antenna is reduced.

Switch to Fig. 5, it is clear that there is a significant difference between radiation patterns when array antenna is with and without metamaterial. When without metamaterial, the directivity of antenna is very low (Fig. 5a). The magnitude of main lode is only 4.21. In addition, the side lobe level is quite high. As a result, the gain of antenna is low. In this case, the gain of antenna is only over 6 dBi. Here, the current distribution in antenna is almost uniform, therefore, the interference between waves is low. Then, the energy flows can not concentrate at place where is contructive interference. This leads to the fact that the gain and directivity of antenna is very low. However, when metamaterial structure on ground plane is used, there is a current re-distribution in antenna and the interference between waves appears. By adjusting current distribution such that there are more and more energy flows at contructive interference, while there is less energy flows at deconstructive interference. Then, an antenna with high directivity and gain is possible, and this has been applied to antenna with the proposed metamaterial structure. Fig. 5b illustrates the radiation pattern of antenna with metamaterial structure. From Fig. 5b, we can see that the directivity of antenna is quite high. This is shown through the main lobe magnitude is 13.3 and the angular width (3dB) is 23.4 degree. Moreover, the side lobe level of antenna is quite low (-6dB). Besides, the efficiency of antenna with the proposed metamaterial structure reaches over 87% while this value without metamaterial is only 73%. It is clear that using metamaterial structure not only improve the bandwidth and gain of antenna, but also it reduces size for antenna.

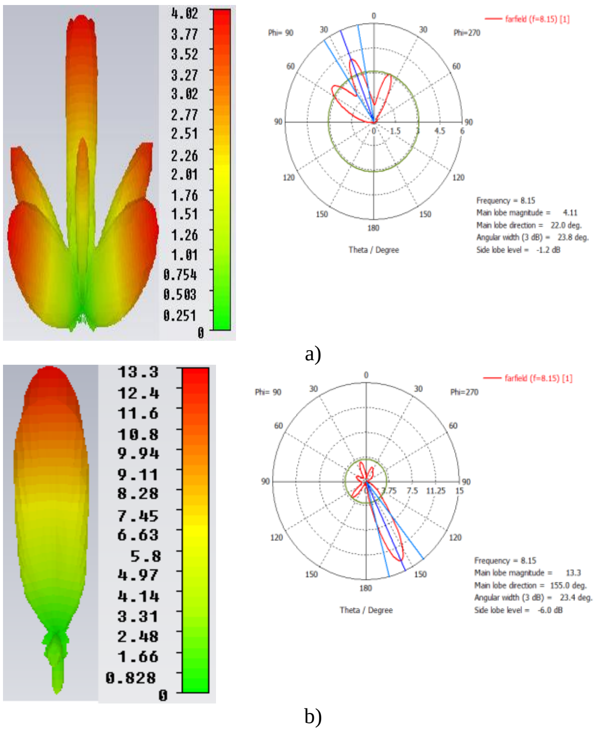


Fig. 5. The difference in radiation pattern of antenna without metamaterial (a) and with memamaterial (b)

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

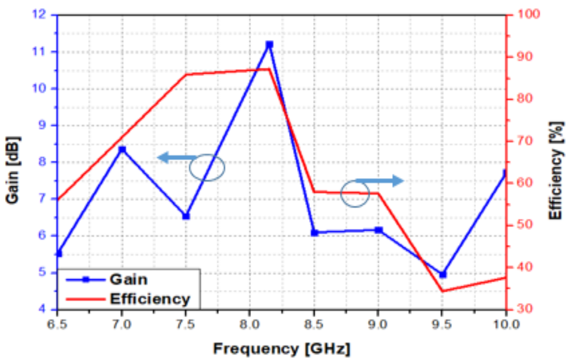


Fig. 6. The gain and efficiency of antenna with the proposed metamaterial structure

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

B. Measurement Results

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

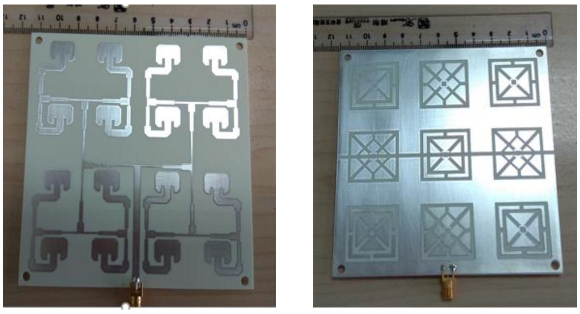


Fig. 7. The fabricated antenna with Roger4350B: (a) top view, (b) back view

Fig. 8 shows the measurement result of antenna reflection coefficient and it is compared to simulation one. From Fig. 8, we can see that although there is a difference between the simulation and measurement results, the operating frequency range of antenna is still guaranteed. Therefore, these result is acceptable. In addition, the impedance bandwidth of antenna is greater than 1.2 GHz corresponding to the bandwidth percentage is approximately 15%. Moreover, the return loss of antenna is very small and this shows that the impedance matching for antenna is very good.

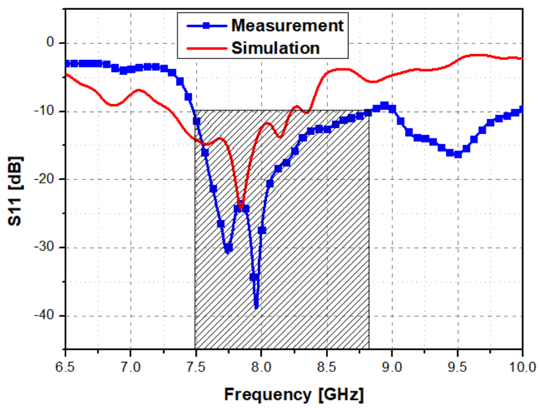


Fig. 8. The measurement result of antenna reflection coefficient

Compare to some announced results, we can see as follows. As in [34], although the antenna including 16 elements is designed at the central frequency of 10.5 GHz, the gain of the antenna is only 10.3 dBi. Similarly, in [35], the 4x4 array antenna is designed at the frequency 10 GHz, but the bandwidth percentage is only 5%. With the above parameters, the array antenna is not enough to satisfy applications in X band. In another research, the efficiency of antenna is only 67% when the frequency of antenna is 35 GHz [36].

V. CONCLUSIONS

In this paper, a new metamaterial structure is proposed and applied successful to improve parameters of a compact array antenna of 4x4 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 is designed on Roger4350B with thickness of 1.524 mm, ε_r = 3.66, tanδ = 0.0037 for frequency range from 7.9 to 8.4 GHz for satellite application. The antenna gets a large bandwidth 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 new metamaterial structure, not only the bandwidth of antenna is improved, but also the gain is enhanced. In addition, the size of array antenna is also reduced through enhancement of the slow-wave factor. Moreover, the paper also analyzes principles for improvement of bandwidth and gain of antenna by using metamaterial structure.

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

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