A Novel Reconfigurable Array Antenna Using Metamaterial Structure

Nguyen Ngoc Lan*, Vu Van Yem
Hanoi University of Science and Technology, No. 1, Dai Co Viet, Hai Ba Trung, Hanoi, Viet Nam
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Abstract

A novel compact 4x3 elements reconfigurable antenna array using PIN-diode for C and X band applications is presented in this paper. By using metamaterial structure on the ground plane, not only antenna's bandwidth is improved, but also the size of antenna is reduced. In addition, the gain of the proposed antenna array is improved by using Metamaterial Reflective Surface (MRS). The proposed antenna array is designed, simulated and fabriacated on FR4 substrate with thickness of 1.575 mm, εr = 4.4 and tanδ = 0.02. The proposed antenna is designed at center frequencies of 6.75 GHz and 9.3 GHz, respectively. The simulation results are obtained in CST Microwave Studio software and are compared to measurement ones.

Keywords: reconfigurable antenna array, pin diode, frequency reconfigurable antenna, microstrip antenna

1. Introduction

Nowadays, the trend of modern wireless communication systems is smart and reconfigurable. In these systems, antenna is an important component whose quality affects directly to transceive progress. Therefore, the antennas must become smart to be able to meet the above requirements. With their advantages, for example, pattern, frequency, polarization can change, the reconfigurable antenna using microstrip technology can satisfy the requirements of modern wireless communication systems. The key features of microstrip antenna are lightweight, small size and easy fabrication. Therefore, microstrip antenna is increasingly widespread application. However, the disadvantages of microstrip antennas are narrow bandwidth, low gain and low efficiency. Hence, the challenge in microstrip antenna design is how to increase the gain, bandwidth and efficiency. Besides, the concept of reconfigurable antennas can be dated back to a 1983 patent of D. Schaubert [1]. Reconfiguring for an antenna can be achieved by changing its frequency, polarization, or radiation characteristics. Today, there are variety of techniques to reconfigure for antenna such as RF-MEMS [2], PIN diodes [3], varactor [4] and so on.

Another aspect very important of the antenna design is also is antenna miniaturization. Today, there are many different antenna miniaturization techniques: magneto-dielectric substrate [5], corrugation [6], loop loading technique [7] and so on. However, the most popular technique is using metamaterial structure. The concept of metamaterials (MTMs) was first investigated by Veselago in 1968 [8]. Metamaterials are broadly defined as artificial effectively homogeneous electromagnetic structures with unusual properties not readily available in nature [9]. Currently, metamaterials are used in many fields. Specifically, in the antenna design, metamaterials are used for: gain and bandwidth enhancement [10][11], antenna miniaturize [12][13], reduction in the peak Specific Absorption Rate (SAR) [14][15].

Besides, with advantages such as broadband and high gain, using array antenna is also one of methods for parameter improvement of antenna. Therefore, to respond all the above requirements, this paper proposes a frequency reconfigurable array antenna using metamaterial structure to improve gain and bandwidth for antenna. Moreover, to enhance antenna's gain, Metamaterial Reflective Surface (MRS) is also used. The selected reconfigurable technique in this paper is using PIN diode. There are some reasons for this selecting such as ease of intergration, fast switching speed. Therefore, PIN diodes have met all requirements of the switching in antenna. The proposed antenna has large bandwidth and it is enough for applications at C and X band. The frequency reconfigurable antenna array is designed in C and X bands, at the center frequencies of 6.75 GHz and 9.3 GHz, respectively. The antenna array includes 12-elements linear array (4x3), and it is based on FR4 substrate with parameters: thickness = 1.575 mm, dielectric constant = 4.4 and tanδ = 0.02.

2 The proposed array antenna

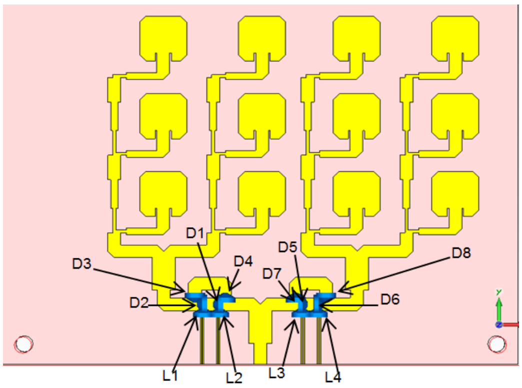
2.1 The model of proposed array antenna

The model of the proposed antenna is shown in Fig. 1. The size of antenna is 120 x 110 mm. The

* Corresponding author: Tel.: (+84) 904.024.242
Email: nnlan@moet.edu.vn

array antenna includes 12 elements and 3 T-junction power dividers. The distance between two antennas is approximately λ0/2 with λ0 is the wavelength in free space. Each element consists of very thin metallic strip (patch) and feed placed on ground plane.

The array antenna based on FR4 substrate on ground plane. Here, D1, D2, ... D8 are PIN Diodes while L1, L2, ... L4 are inductors. In here, inductors (L1 – L4) is added to block alternating current.



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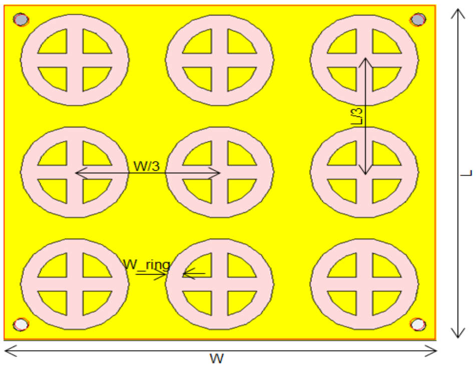


b)

Fig. 1. The model of proposed antenna: top (a) and bottom (b)

2.2 Array antenna design

2.2.1 Design of array antenna

The proposed antenna model is shown in Fig. 2. The antenna includes 12 elements and the model of each element is shown in Fig. 3. In here, the parameters of an element is calculated as in [16]. Table 1 shows parameters of an element in array. The distance between antenna and MRS is h = 20 mm while the size of antenna is 110 x 120 mm.

With unusual properties that common materials do not have such as reversal of Doppler effect, reversal of Snell's law, metamaterial can improve simultaneously many parameters for antenna, for example: gain enhancement, bandwidth improvement, miniaturization, mutual coupling reducing, and so on. For the above reasons, this paper uses metamaterial structure in ground plane to enhance bandwidth for antenna.

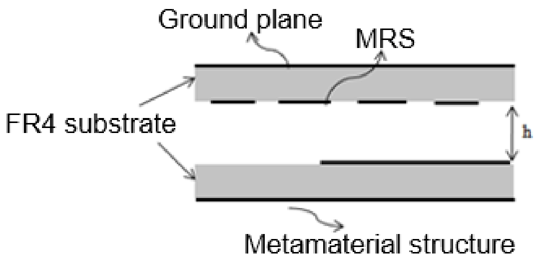


Fig. 2. The model of antenna

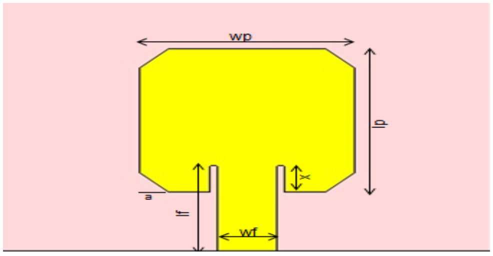


Fig. 3. An element in array

The distance between rings in ground is 40 mm (equal to W/3) and 36.67 mm (equal to L/3). Using metamaterial structure on ground plane creates parasitic capacitors and inductors and this also helps to create consecutive cavity resonators. As a result, the bandwidth of antenna is enhanced. We know that the resonant frequency of antenna is given by:

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (8)$$

It is clear that the resonant frequency of antenna is descrease when L and C values is increase. This means that the antenna size is reduced.

Table 1. The parameter of an element in array

Paramet	*wf*	*lf*	*a*	*lp*	*wp*	*x*
Valu	*3.0*	*6.5*	*1.5*	*11*	*11*	*2*

Besides, the impedance matching for antenna is illustrated in Fig. 4. To impedance matching, this paper uses quarter-wave transformers to transform a large input impedance to 50 ohms line, by using equation:

$$Z_T = \sqrt{Z_0 Z_{in}} \quad (9)$$

Where: Z_{in}: input impedance of line, Z_0: characteristic impedance

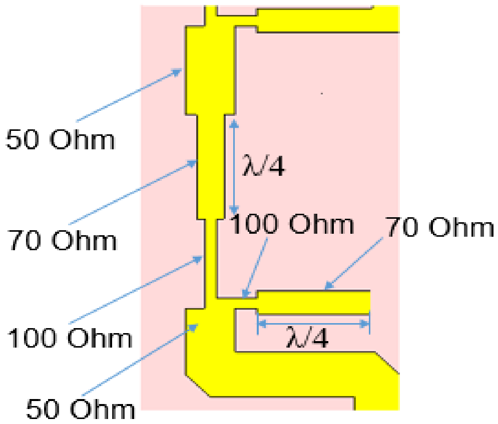


Fig. 4. The impedance matching for antenna

Currently, the major types of reconfiguration techniques that can be used to implement reconfigurable antennas such RF-MEM, PIN diode, varactor, and so on. However, PIN diode is the best candidate thanks to some reasons, for example: easy to integrate, fast switching and small size. Therefore, PIN diodes is slected to achieve the reconfiguration for antenna in this paper. Moreover, the reconfiguration is achieved by changing the length of the transmission line. This is achieved by adjusting the status of the PIN diode: ON/OFF. Here, we design and implement an array antenna that is composed of 12 elements. The resonant frequency of the array antenna is inversely proportional to the size of array. When we change the length (feeding), the geometry of the total array change, so the resonant frequency changes. In RF circuits, PIN Diodes operate as a contact with two modes: ON and OFF. When the state is ON, they act as a resistor with very small value. In contrast, when the state is OFF, they act as a resistor with very large value.

By changing status of PIN Diodes, we obtain equivalent frequencies. There are different types of PIN diode. However, to suit with design requirements, MACOM-MA4AGBLP912 is chosen for simulation. Lumped elements are used in modeling the PIN diode in CST Microwave Studio.

2.2.2 Metamaterial Reflective Surface (MRS)

To increase the antenna's gain, this paper uses MRS. The MRS is a periodic structure as shown in Fig. 5. The MRS is built on FR4 with thickness h = 1.6, dielectric constant = 4.4 and tanδ = 0.02. The MRS includes a substrate FR4, a ground layer and a metamaterial surface with thickness t = 0.035 mm. The size of MRS's substrate is 110 x 120 mm. The MRS is composed of 3×3 unit cells. The resonant frequency can adjust by changing of unit cell and grid dimensions. Table 2 presents the parameters of MRS.

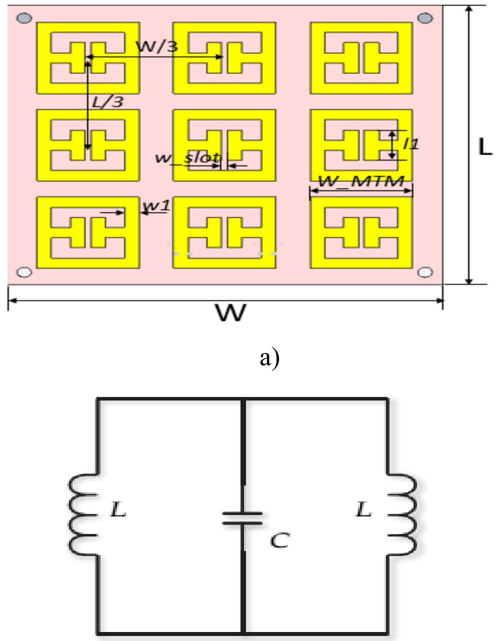


Fig. 5. MRS structure (a) structure and equivalent circuit of unit cell (b)

According to the quasi-static theory, the total capacitance formed between gaps is [17]:

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d}(F) \quad (10)$$

where ε_0 and ε_r are the permittivity of free space and the relative permittivity, respectively. A is the cross-sectional area of the gap; and d is the gap length.

Here, MRS behave likes a reflector and it acts as a Frequency Selective Surface (FSS). Therefore, it behave likes filters and it has equivalent circuit as in Fig.5. By altering its size, we will obtain equivalent values of L and C.

Table 2. The parameters of MRS

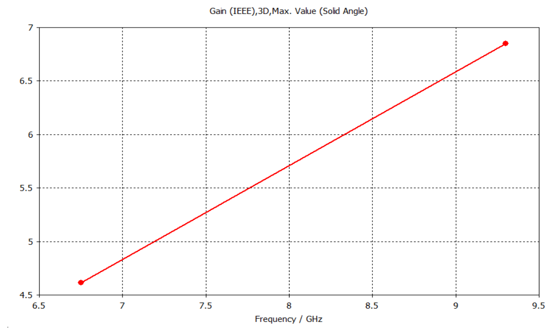
Parame	*W_MTM*	*w1*	*w_slo*	*L*	*W*	*l1*
Value	*28*	*8*	*1.6*	*110*	*120*	*12*

3. Simulation and measurement results

3.1 Simulation results

Fig. 6 illustrates the difference between radiation pattern antenna with MRS and antenna without MRS.

It is clear that the main lobe magnitude of antenna is improved when antenna uses MRS. The antenna's gain was increased from 6.85 dB to 11 dB.



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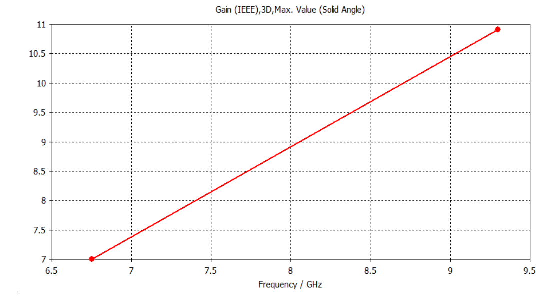


Fig. 6. The difference between radiation pattern of antenna without MRS (a) and with MRS (b)

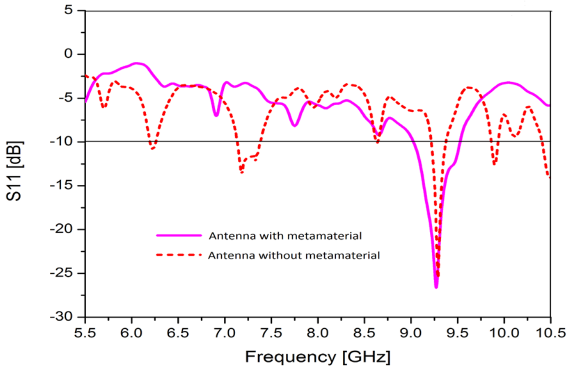


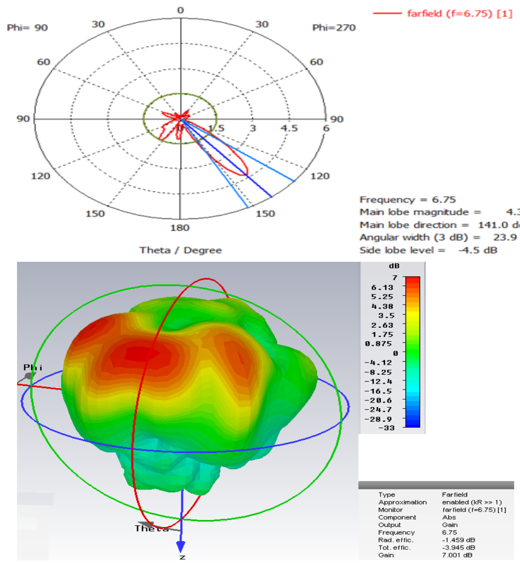
Fig. 7. The difference between impedance matching of antenna without metamaterial and with metamaterial

When electromagnetic energy is incident on a FSS, currents are induced on the conducting elements. These induced currents then re-radiate EM waves from these conducting elements. It is clear that the back lobe and side lobe is reduced, which helps focus energy in main lobe. This leads to increase gain and directivity of antenna. Fig. 7 illustrates the difference between using metamaterial structure on ground plane.

From Fig. 7, we can see that the antenna's bandwidth is improved significantly. The antenna's bandwidth is increased from 150 MHz to 500 MHz when using metamaterial structure. This shows that using metamaterial is a good solution. By using metamaterial structure on ground plane, the consecutive cavity resonators are created. This helps to enhance bandwidth for antenna.

Fig. 8 shows far field of antenna at center frequencies of 6.75 GHz and 9.3 GHz, respectively.

From Fig. 8, we can see that the antenna's gain is 7 dB and 11 dB at center frequencies of 6.75 GHz and 9.3 GHz, respectively. In addition, the angular width 3 dB is 32 degrees and 15.4 degrees at center frequencies of 6.75 GHz and 9.3 GHz, respectively. This suggests that the antenna's directivity is quite high.



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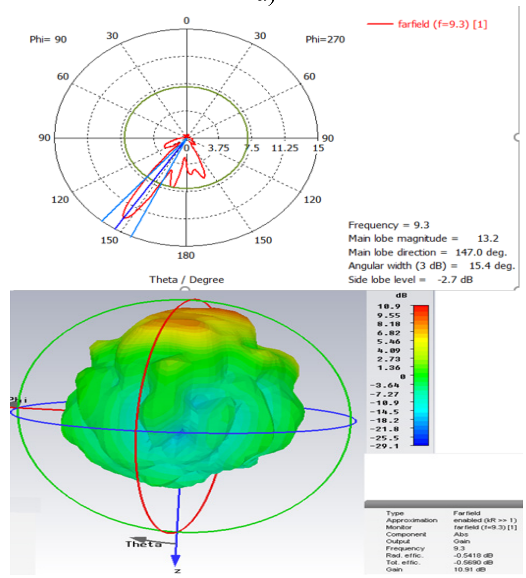

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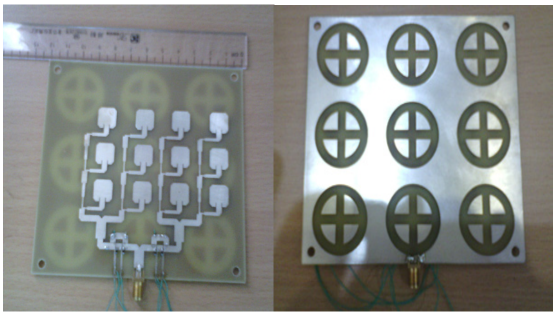
Fig. 8. The radiation pattern of antenna at center frequencies of 6.57 GHz (a) and 9.3 GHz (b)



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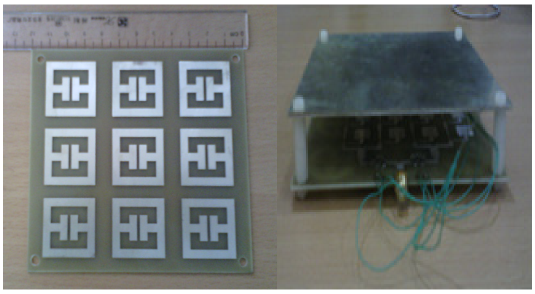

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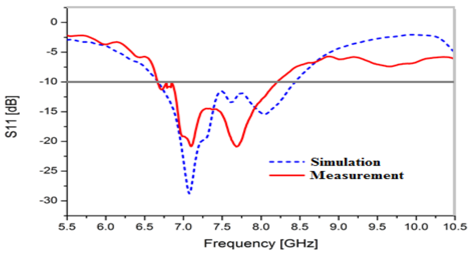
Fig. 9. The fabricated antenna: array antenna and ground plane (a) and MRS and antenna's model (b)



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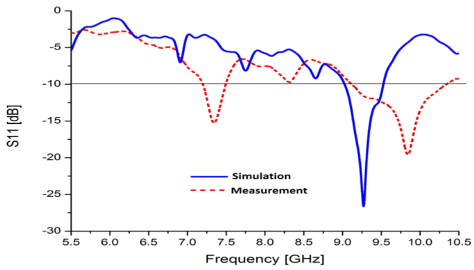

b)

Fig. 10. The simulation and measurement results at frequencies of 6.75 GHz (a) and 9.3 GHz (b)

3.2 Measurement results

The antenna is fabricated on FR-4. The photo for fabricated antenna is shown in Fig. 9. Fig. 9(a) presents array antenna and ground plane with metamaterial structure while Fig. 9(b) shows MRS and antenna's model. The antenna is measured by Anritsu 37369D Vector Network Analyzer at University of Engineering àn Technology – Vietnam National University. Due to the limitation in measurement devices, the pattern measurement for antenna can not implement. Therefore, the measurement for antenna is only performed with S-parameters.

Fig. 10 illustrates measurement results of antenna and compairs with simulation results for two reconfigurations.

From Fig. 10, we can see that although there is a difference between simulation and measuarement results, the frequency bands for antenna operation are still guaranteed. Therefore, these results are acceptable. There are some reasons caused the above difference such as solder for SMA connector port and PIN Diodes, the deviation in fabrication, the deviation of substrate (dielectric constant, thickness, ...), effect of wires (power supply for PIN Diodes). In addition, the stability of parameters in FR4 is very low while the parameters of substrate significantly affect to the parameters of antenna. Therefore, this is also one of reasons for the above difference. However, the bandwidth still covers from about 6.6 GHz to 8 GHz and from 9 GHz to greater than 10 GHz and these bandwidths are enough for applications in C and X bands.

Compared to some published papers, we can see as follow. In [18], although the antenna includes 16 elements and is designed at central frequency of 11 GHz, the gain of antenna is only 8.1 dB. In another study, an array antenna is designed at frequency of 10 GHz including 16 elements, but the bandwidth percentage is only 5% [19]. Similarly, even when the antenna including 256 elements is designed at frequency of 60 GHz, but the bandwidth percentage of antenna is only 6.5% [20]. It is clear that with the above parameters, the antennas can not satisfy for current applications. Therefore, by using metamaterial and MRS, not only the bandwidth of antenna is improved, but also the gain is enhanced.

4. Conclusions

In this paper, we have designed, simulated and fabricated a frequency reconfigurable antenna array of 4x3 elements. By using metamaterial structure on ground plane and MRS, the proposed antenna's gain and bandwidth is improved. The key limitations of microstrip antenna, that are gain and bandwidth which are improved significantly. The antenna's gain is 7 dB and 11 dB at center frequencies of 6.75 GHz and 9.3 GHz, respectively. The bandwidth of antenna covers from approximately 6.6 GHz to about 8 GHz and from 9 GHz to greater than 10 GHz, so this bandwidth is enough for broadband applications.

With advantages such lightweight, small size, low cost and easy fabrication, microstrip antenna can widely apply in practice.

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