Dual-Band and Dual-Polarized Electrically Tunable Reconfigurable Reflectarray Antenna

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Abstract **─** In this paper, a dual-band and dual-polarized electrically tunable reconfigurable reflectarray antenna (RRA) is proposed, fabricated and measured for the beam-scanning performance. The RRA element, a single layer structure with two split-rings and a pair of varactor diodes, can be electrically tuned to work at the two orthogonal polarization modes of the incident electric field at 4.2GHz and 6.5GHz, respectively. Besides, the range of the phase compensation of the element is over 300° at the two polarization modes. Then, a RRA with 15×15 elements is designed, fabricated and measured to prove the validity. The main beam direction can be controlled by tuning these varactor diodes of the RRA and the beam-scanning range is from -60° to 60°. The experimental results and simulation results are in good agreement to prove the correctness and feasibility of the design of the novel dual-band and dual-polarized electrically tunable RRA.

Index Terms **─** Beam-scanning, electrically tunable, reconfigurable reflectarray antenna, varactor diodes.

I. INTRODUCTION

Microstrip reflectarray antennas, with the merits of low profile, low cost, small volume, high gain and accurate main beam direction, etc., are rapidly becoming an attractive alternative in the modern radar and satellite communication system. Some researchers alter the main beam direction by changing the size of reflectarray antenna unit, changing the length of phase delay line and so on [1].

However, these methods have an obvious shortcoming that it is not possible to achieve beam-scanning adaptively in the actually needed direction [2]. Furthermore, the conventional microstrip reflectarray antennas always only radiate in a fixed direction after fabricated. In order to meet the increasing demand of the antenna system, more reconfiguration properties are obviously studied to reduce the amount of antennas and improve the utilization ratio of antenna [3-4].

Besides, everyone knows, the base station antenna has radiation blind area of the communication system. One solution is to add antennas but the cost of the whole system is greatly increasing. The RRA may be a better choice to solve the signal coverage problem. However, it is still a challenge to design a RRA with much wider beam-scanning range and higher antenna efficiency [5-6]. There has been a series of researches and developments on the novel reconfigurable elements and RRAs. Some researchers utilize the electronically tunable materials, such as liquid crystal, graphene and other new functional materials, to obtain the beam-scanning characteristic.

Thus, it can be seen that the RRA has attracted more considerable attentions [7]. The RRA, just by changing the voltage of the external active devices, can achieve adaptive, flexible beam-scanning and reconfiguration properties [8-9]. Recently, the lumped switches are widely used in most of the design of the RRA, especially the PIN diode and the varactor diode because they are simple and don't need special process technology. Hence, the multifunctional RRA has emerged as an up-and-coming alternative in more areas in the future. But most of these studies only concentrate on single working frequency or single polarization mode [10-12].

In our work, a dual-band and dual-polarized electrically tunable RRA is proposed to obtain continuous controllable beam-scanning performance. The RRA consists of 15×15 elements etched on the dielectric substrate. Section II briefly describes the working principles of the reflectarray antenna. In Section III, a dual-band and dual-polarized RRA element is proposed working at two orthogonal polarization modes of the incident electric field at 4.2GHz and 6.5GHz, respectively. Specifically, in Section IV, a dual-band and dual-polarized RRA is simulated, fabricated and tested. The simulation results and measurement results are in good agreement to verify the effectiveness of the design of the novel RRA. Finally, Section V concludes this work.

Submitted On: September 28, 2018
Accepted On: December 14, 2018

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II. PRINCIPLES OF REFLECTARRAY ANTENNA

For the microstrip reflectarray antenna, the key is the design of the element [13]. Once the determination of feed's position, the phase caused by the distance of the feed between the reflecting antenna unit is determined. While the element of the reflectarray antenna meets the certain amplitude and phase conditions, the reflected beam can radiate in the specified direction. In order to obtain the needed main beam direction, the key is to calculate the phase compensation for every element.

As shown in Fig. 1, the antenna contains $M \times N$ units, $\vec{r}_f$ is the position of the feed and $\hat{u}_0$ is the main beam direction. The reradiated electromagnetic wave in an arbitrary direction can be calculated by:

$$E(\hat{u}) = \sum_{m=1}^{M}\sum_{n=1}^{N} F(\vec{r}_{mn}\cdot\vec{r}_f)A(\vec{r}_{mn}\cdot\hat{u}_0)A(\hat{u}_0\cdot\hat{u})\cdot\exp\phi\,, \quad (1)$$

$$\phi = -jk_0(|\vec{r}_{mn}-\vec{r}_f| - \vec{r}_{mn}\cdot\hat{u}) + j\alpha_{mn}\,, \quad (2)$$

where F is the function of the radiation pattern of the feed. A is the function of the radiation pattern of the array unit. $\vec{r}_{mn}$ is the position of every element and α_{mn} is the phase compensation of the i^{th} cell. Based on the analyses above, the specific calculation process is given as below.

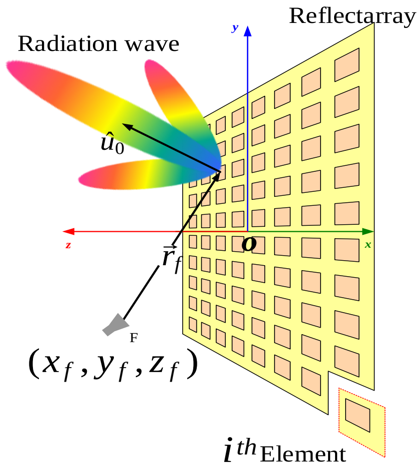


Fig. 1. Coordinate of the reflectarray.

If the antenna radiates in the desired direction, the cells must meet the equal phase delay path from the feed to the equiphase surface in Fig. 2. In other words, the phase compensation from the feed to each cell ϕ_f, the phase compensation of every cell ϕ_{mn} and the phase compensation from every cell to the equiphase surface ϕ_r should meet:

$$\phi_f + \phi_{mn} + \phi_r = 2n\pi \quad (n = 1,2,3...)\,. \quad (3)$$

In order to calculate ϕ_{mn}, we firstly have to calculate ϕ_f and ϕ_r. (x_f, y_f, z_f) and (x_{mn}, y_{mn}, z_{mn}) represent the coordinates of the feed and the element, respectively. d_{mn}, the distance between the feed and the element, is given by:

$$d_{mn} = \sqrt{(x_{mn}-x_f)^2 + (y_{mn}-y_f)^2 + (z_{mn}-z_f)^2}\,, \quad (4)$$

so ϕ_f can be calculated by:

$$\phi_f = k_0 d_{mn}\,, \quad (5)$$

where $k_0 = 2\pi/\lambda_0 = 2\pi f/c$ is the propagation constant in vacuum; λ_0 is the wavelength in vacuum; c is the speed of light in vacuum; f is the working frequency of the antenna; (θ_0, φ_0) represents the main beam direction. Based on the theory of array antenna, ϕ_r is reckoned by:

$$\phi_r = -k_0\sin\theta_0\cos\varphi_0 x_{mn} - k_0\sin\theta_0\sin\varphi_0 y_{mn}\,. \quad (6)$$

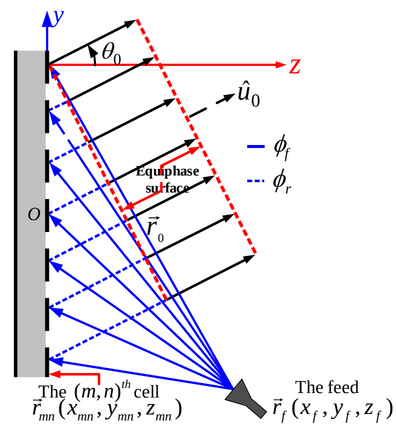


Fig. 2. Phase delay path of the reflectarray.

In the end, we can get the phase compensation ϕ_{mn} by taking Equations (4), (5) and (6) into Equation (3). Up to now, if we already know the operating frequency f, the main beam direction (θ_0, φ_0), the coordinate of the feed (x_f, y_f, z_f), and the coordinate of the cell (x_{mn}, y_{mn}, z_{mn}), the phase compensation ϕ_{mn} of each cell will be computed and the reflectarray antenna can form the main beam in the desired direction.

III. DUAL-BAND AND DUAL-POLARIZED RRA ELEMENT

In this part, a dual-band and dual-polarized RRA element is presented, as Fig. 3 shows, which mainly consists of two split-rings and two varactor diodes. The direction of the opening of the inner ring is rotated by 90° compared with the outer one. The unit is etched on the dielectric substrate and the bottom is the metal ground. The permittivity of the dielectric substrate is 2.65 and other geometrical parameters of the element are given in Table 1. Numerical analyses and optimizations of this unit have been done in HFSS 15.0. The Floquet port and the infinite periodic boundary condition are adopted.

The element makes the point, dual-band and dual-polarized electrically tunable and beam-scanning performances, by adjusting the capacitance of varactor diodes not changing the structural parameters. When the polarization direction of the electric field of the incident wave is along the X axis and the Y axis, the operating frequencies are at 4.2GHz and 6.5GHz, respectively.

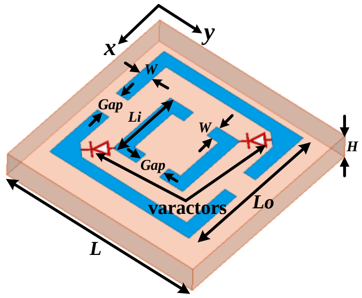
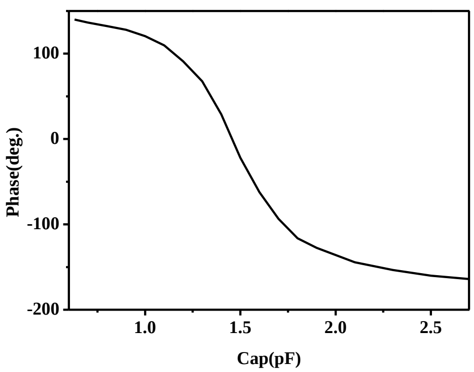
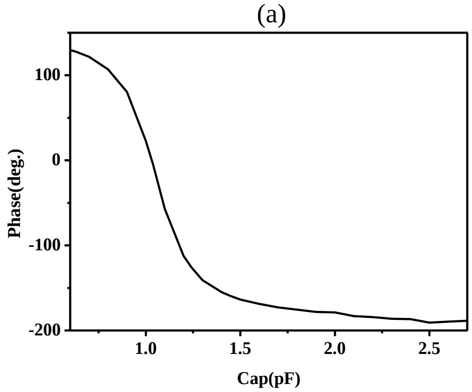


Fig. 3. Geometry of the dual-band and dual-polarized RRA element.



(a)



(b)

Fig. 4. Phase compensation curve: (a) at 4.2 GHz and (b) at 6.5GHz.

As seen in Fig. 4, it can be found that the range of the phase compensation is over 304° and 318° for each polarization mode. It is worthwhile to point out that the phase compensation of the cell can be changed through adjusting the capacitance of varactor diodes.

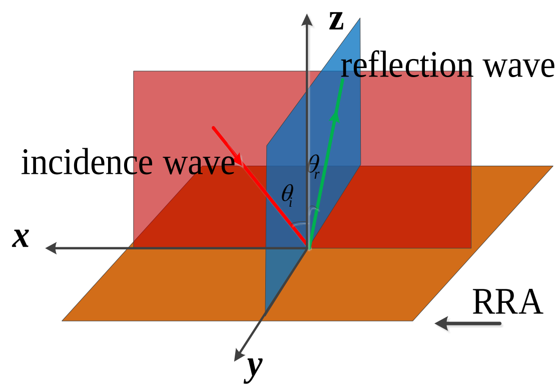
As we expected, the dual-band and dual-polarized element can work at different polarization modes at different operating frequencies. All in all, the unit is a crucial role in the design of the dual-band and dual-polarized RRA.

Table 1: Parameters of the RRA element

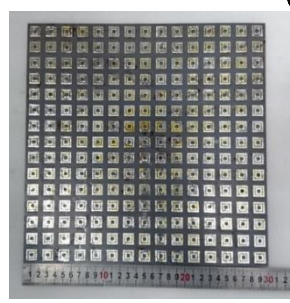
Parameter	Size (*mm*)	Parameter	Size (*mm*)
L	20	*W*	1.8
Lo	14	*Gap*	0.2
Li	10	*H*	0.5
h	0.25		

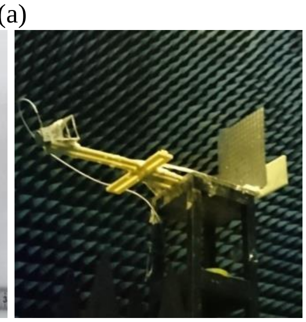
IV. DESIGN AND ANALYSIS OF THE RRA

Based on the simulations of the dual-band and dual-polarized element, a RRA is designed in this section, given in Fig. 5, which works at two polarization modes at different frequencies. The dual-band and dual-polarized RRA is composed of 15×15 cells. The size of the antenna is 300×300*mm*. The incident wave is in the *xoz* plane; the reflection wave is in the *yoz* plane. The direction of the incidence wave $(\theta_i, \varphi_i) = (20°, 0°)$ and the direction of the reflection wave $(\theta_r, \varphi_r) = (\theta_r, 270°)$.



(a)

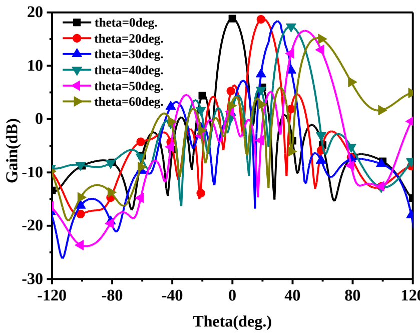




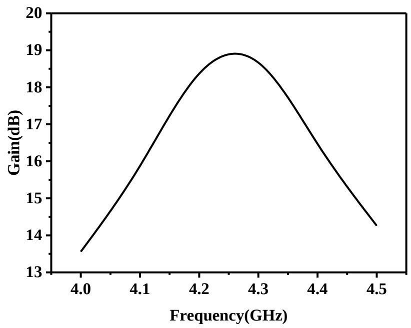
(b) (c)

Fig. 5. (a) The coordinate of the simulation, (b) the fabricated RRA, and (c) the experimental scene.

According to the theories of the reflectarray antenna mentioned in Sec. II, we only need to determine the capacitance of each unit to acquire different main beam directions due to the relationship between the capacitance of the varactor diodes and the phase compensation. The angle of the beam-scanning θ_r is supposed from -60° to 60°.



(a)



(b)

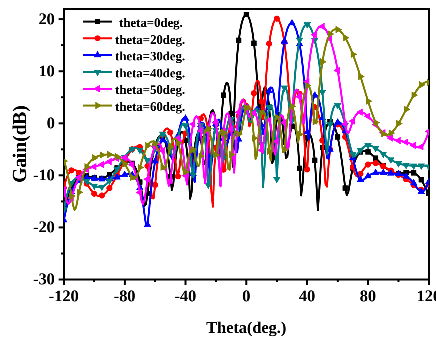
Fig. 6. (a) The gain of the RRA at 4.2GHz, and (b) the gain of the RRA when $(\theta_r, \varphi_r) = (20°, 270°)$.

Table 2: Characteristics of the RRA at 4.2GHz

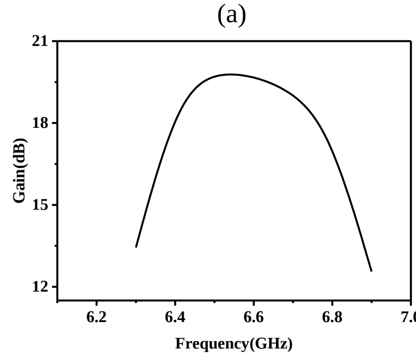
Direction	Gain (dB)	FSLL (dB)	Error
(0°,270°)	20.94	7.51	0°
(20°,270°)	20.12	4.62	0°
(30°,270°)	19.25	3.11	0°
(40°,270°)	19.00	3.54	0°
(50°,270°)	18.67	1.58	0°
(60°,270°)	18.03	7.25	0°

The dual-band and dual-polarized RRA can work at the horizontal polarization mode and the perpendicular polarization mode. When the incident wave is at the horizontal polarization mode, the direction of the electric field of the incident wave and the incident plane are in the same plane, the operating frequency is 4.2GHz. The reflection angle θ_r is from 0° to 60° and the 3dB relative bandwidth is approximately 4.8% while θ_r = 20° in Fig. 6. In order to compare the characteristics of the reflectarray more intuitively, Table 2 gives the characteristics in different radiation directions when the operating frequency is 4.2GHz. The gain of the RRA decreases slowly at horizontal polarization mode.

Besides, when the incident wave is at the perpendicular polarization mode, the direction of the electric field of the incident wave is perpendicular to the incident plane, the operating frequency is 6.5GHz. The reflection angle θ_r varies from 0° to 60° and the 3dB relative bandwidth is approximately 6.7% while θ_r = 20°, as shown in Fig. 7. From Table 3, the gain of the RRA also decreases slowly at the perpendicular polarization mode. It is clear to see that the RRA can provide two selectable states, at two orthogonal polarization modes at 4.2GHz and 6.5GHz. The beam directions of the RRA are consistent with the presented directions and these simulations confirm the feasibility of the design. The RRA in this section can achieve the frequency agility and polarization reconfigurable feature. Furthermore, it can achieve bean-scanning through controlling the capacitances of varactor diodes.



(a)



(b)

Fig. 7. (a) The gain of the RRA at 6.5GHz, and (b) the gain of the RRA when $(\theta_r, \varphi_r) = (20°, 270°)$.

Table 3: Characteristics of the RRA at 6.5GHz

Direction	Gain (dB)	FSLL (dB)	Error
(0°,270°)	18.90	6.02	0°
(20°,270°)	18.82	6.35	0°
(30°,270°)	18.43	7.19	0°
(40°,270°)	17.37	5.72	0°
(50°,270°)	16.55	5.11	1°
(60°,270°)	15.19	5.93	2°

In order to verify our design, the dual-band and dual-polarized RRA prototype is fabricated and experimentally tested for proof of principle. The incident wave are set in the *xoz* plane, the direction of the incident wave $(\theta_i, \varphi_i) = (20°, 0°)$, and the direction of the reflection wave $(\theta_r, \varphi_r) = (20°, 270°)$. From Fig. 8 and Fig. 9, the main beam direction is a bit inconsistent between the simulation result and the measured result. The measured gain is less than the simulated result in Fig. 10 and Fig. 11. The reason may be the deviation in physical processing. It is believed that the design of the dual-band and dual-polarized RRA is reasonable and valid.

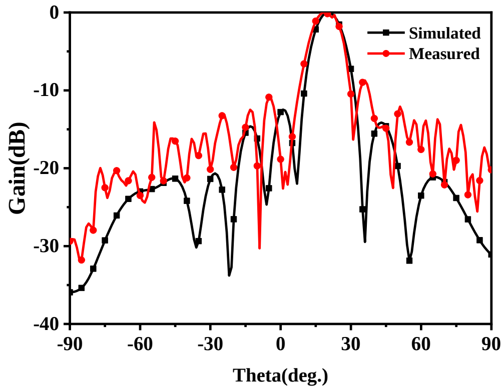


Fig. 8. The gain of the RRA at 4.2GHz.

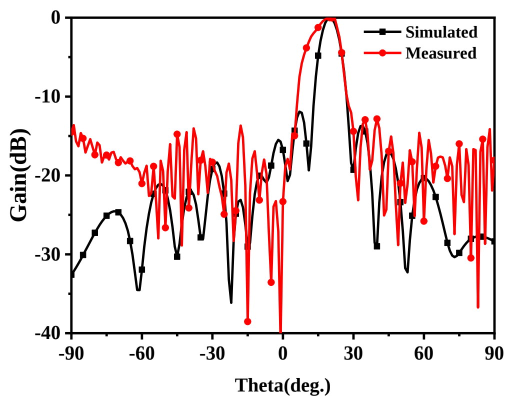


Fig. 9. The gain of the RRA at 6.5GHz.

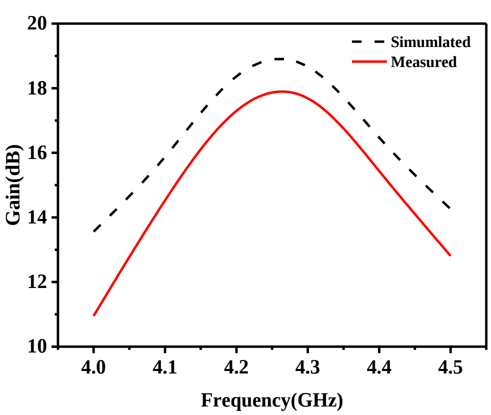


Fig. 10. The gain when at perpendicular polarization mode and $(\theta_r, \varphi_r) = (20°, 270°)$.

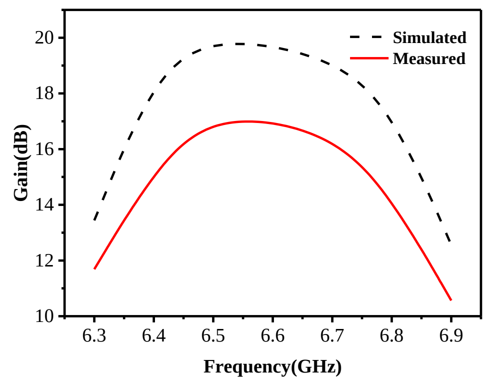


Fig. 11. The gain when at perpendicular polarization mode and $(\theta_r, \varphi_r) = (20°, 270°)$.

V. CONCLUSION

A dual-band and dual-polarized electrically tunable RRA is thoroughly investigated in our work. At dual-band, 4.2GHz and 6.5GHz, the polarization mode is also different. The dual-band and dual-polarized RRA is designed by utilizing the novel element to achieve continuous beam-scanning feature. In Sec. IV, the dual-band and dual-polarized RRA is fabricated. The simulated results and measured results are in good consistence to testify the good properties of the proposed antenna. The multifunctional RRA, which has notable potentials in offering interesting functionalities, may be given special attention in the radar and communication system to reduce the amount of antennas and the decrease of the complexity of the system.

ACKNOWLEDGMENT

This work is supported by Shaanxi Outstanding Youth Science Foundation and National Key R&D Program of China, and supported by the Science and Technology Project of State Grid Corporation of China "Research on Ten-meter level Microwave Radio wireless power Transmission Technology".

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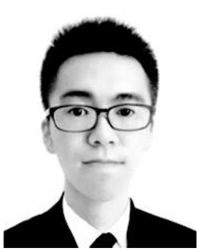

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