Progress In Electromagnetics Research Letters, Vol. 106, 97–102, 2022

PIN Diodes Loaded 1-Bit Cylindrical Reconfigurable Reflectarray Antenna

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Abstract—In this paper, we propose a phase compensation method for cylindrical reconfigurable reflectarray antennas and design a cylindrical reconfigurable reflectarray antenna (CRRA) for generating steering beams. Using a PIN diode loaded reflectarray element, 1-bit reflection phase-shift with phase difference of 180° can be realized. The cylindrical reflectarray consists of 16 × 18 unit cells whose reflection phase shifts are controlled by bias network independently. Using phase quantization, the reflectarray can generate the desired phase distributions for steering beams. Both simulated and measured results show that the proposed CRRA can achieve beam scanning in ±40° angle range. In addition, the measured gain reaches 20.5 dBi, and 1 dB gain bandwidth is 6.9%. The proposed cylindrical conformal reconfigurable reflectarray antenna can provide a reference for the application of the conformal scenario of a reconfigurable reflectarray antenna in the future.

1. INTRODUCTION

The development of modern wireless communication systems requires antennas to develop in the direction of low latency, high bandwidth, and multi-functions. Since reconfigurable reflectarray antennas (RRAs) have the advantages of excellent integration, flexibility, and low cost, they have been research hotspot for years [1–4]. Compared with traditional phased arrays [5, 6], reconfigurable reflectarray does not need complex and expensive feed networks. In addition, compared with varied-size reflectarray antenna [7], RRA can change the resonant length or electric field distribution of the antenna by means of mechanical devices or electronic switch regulation, without changing physical dimensions of the antenna. As a result, the frequency characteristics or radiation features of RRA can be dynamically adjusted according to the operating environment.

PIN diodes and varactor diodes are usually loaded on RRA elements to realize reconfigurable reflection phase-shifts. Specifically, a reflectarray element loaded with PIN diodes is proposed in [8], and a 10×10 planar array is designed to achieve the beam scanning within ±50°. In [9], an electronically switching-beam reflectarray antenna which uses PIN diodes as switching device is designed to realize beam scanning of ±5° on a specific slope. In addition, a varactor diode based reflectarray element is proposed in [10], and a 3 × 15 planar antenna is designed to achieve ±20° beam scanning. Moreover, 1-bit reflectarray arrays are proposed in [11] to achieve beam scanning, which can achieve beam scanning in the range of ±60°. In [12], a multi-layer 1-bit reflectarray unit is proposed to achieve beam scanning in the ±40° range. For the varactor diodes loaded RRA element, its reflection phase-shift can be adjusted continuously by loading different voltages on two sides of varactor diode to obtain different capacitance values. In [13], a two-layer reflective cell is proposed, and a phase range of 318° is achieved by loading a varactor diode in the lower substrate patch and ground. Furthermore, the beam scanning range of ±40° is achieved. In [14], a continuous phase shift range of 360° is realized by loading

Received 19 July 2022, Accepted 30 August 2022, Scheduled 13 September 2022
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varactor diodes on a reflectarray, and it has a beam scanning range of ±40°. However, the above mentioned literature is all based on planar reconfigurable reflectarray antennas. With the introduction of the concepts of 5G and the Internet of Things, there is an increasing trend towards the need for conformal reflectarray antennas which can be integrated with various surfaces of communication systems. Conformal antennas [15, 16] can be deployed more flexibly on top of their conformal counterparts and can make full use of limited space or existing infrastructure, offering users a faster, less obtrusive, and more comfortable network experience. The design of conformal reconfigurable reflectarray antennas is therefore of great importance. By combining reconfigurable reflectarray with conformal technologies, a cylindrical reconfigurable reflectarray antenna based on PIN diodes at 5.8 GHz is designed, and a prototype with 16 × 18 elements is simulated and measured. Both results show that the cylindrical CRRA can realize steering beams in the scanning angle range of ±40°. The proposed CRRA can be applied in satellite communication systems and wireless communication systems.

2. ELEMENT DESIGN AND SIMULATION

The topology of the conformal reconfigurable reflectarray element is shown in Figure 1. It is composed of two layers of FR4 glass fiber epoxy laminate with a top metal layer and a bottom layer. The top metal layer is a slotted square patch with symmetrical cuts, and the two slotted patch is connected by a PIN diode. When the PIN diode is from ON state to OFF state, the resonant characteristics change to produce a phase difference of 180°. In order not to affect the radiation performance of the CRRA unit cell, we place two bias points on the positions where electric field is almost zero. Next, we connect one of the bias points to the bottom bias line of the lower FR4 substrate through a metallized via. The other bias point is connected to the bottom layer of the upper FR4 substrate through the metallized

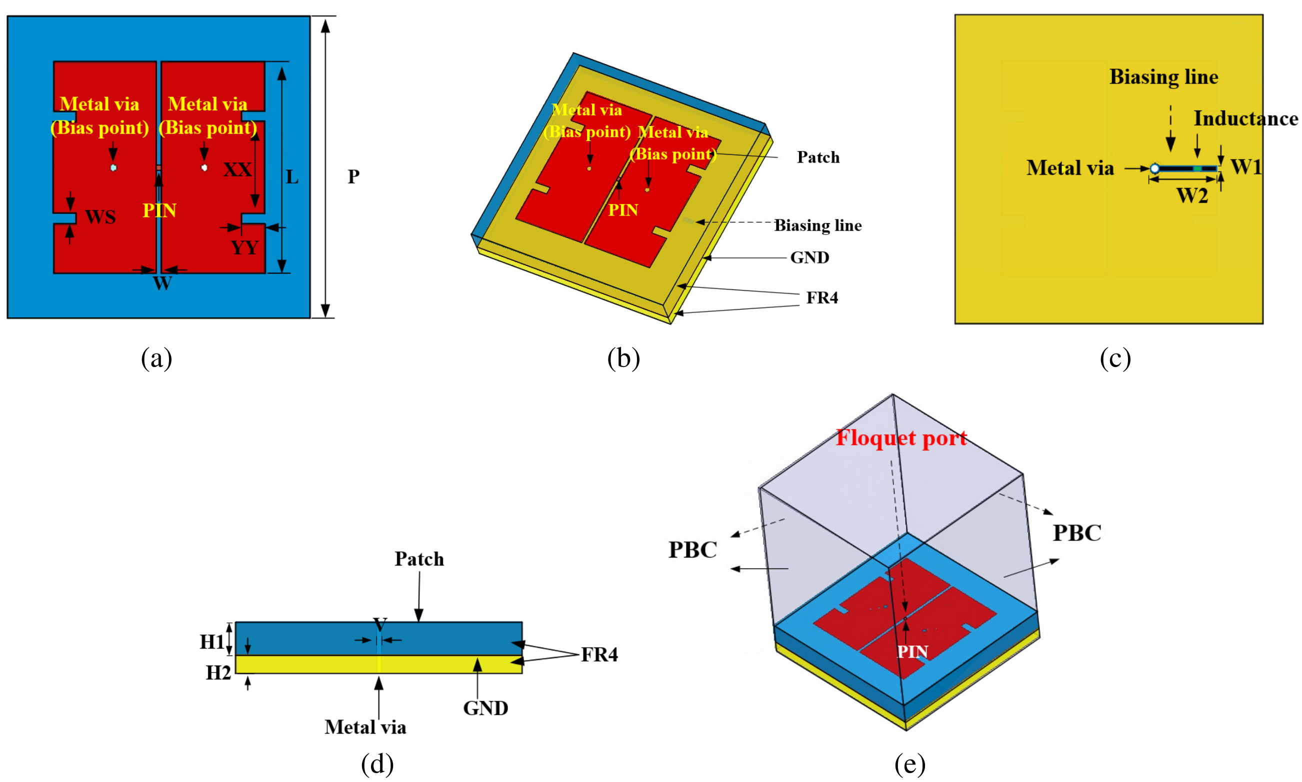

Figure 1. Topology of proposed CRRA element: (a) top view, (b) perspective view, (c) bottom layer, (d) side view. ($P = 26.5$ mm, $L = 18.5$ mm, $W = 0.42$ mm, $H1 = 3$ mm, $H2 = 1.6$ mm, $R1 = 0.3$ mm, $P1 = 0.5$ mm, $P2 = 5$ mm, $P3 = 0.6$ mm, $XX = 5$ mm, $YY = 2$ mm, $WS = 1$ mm). (e) Full wave simulation model.

via. To reduce the effect of RF signals on the bias network, we put an inductor with 47 nH through bias line to ensure the isolation between DC bias lines and RF signals.

In addition, the PIN diode shown in Figure 1 is Skyworks SMP1340-040LF, which has a low insertion loss and a wide operating bandwidth of 10 MHz–10 GHz. When PIN diode is in ON state, it can be equivalent to the combination of a resistor $R1$ and an inductor $L1$ in series ($R1 = 1\,\Omega$, $L1 = 450\,\text{pH}$), as shown in Figure 2(a). When PIN diode is in OFF state, its equivalent circuit is a series branch with one resistor $R2$, one inductor $L2$, and one capacitor C ($R2 = 10\,\Omega$, $L2 = 450\,\text{pH}$, $C = 0.16\,\text{pF}$) which is shown in Figure 2(a). We simulate the reflectarray element with Floquet port excitations and infinite boundary conditions, as shown in Figure 1(e). The simulated reflection coefficients are shown in Figure 2(b). It can be seen that the reflection phase of the CRRA unit cell at 5.8 GHz is $+35^\circ$ and -145° when the PIN diode is ON and OFF, respectively. This means that the reflection phase difference between ON state and OFF state of PIN diode is 180° at 5.8 GHz. In addition, the reflection loss at operational frequency band is less than 2.5 dB whether the state of PIN diode is ON or OFF which is shown in Figure 2(b).

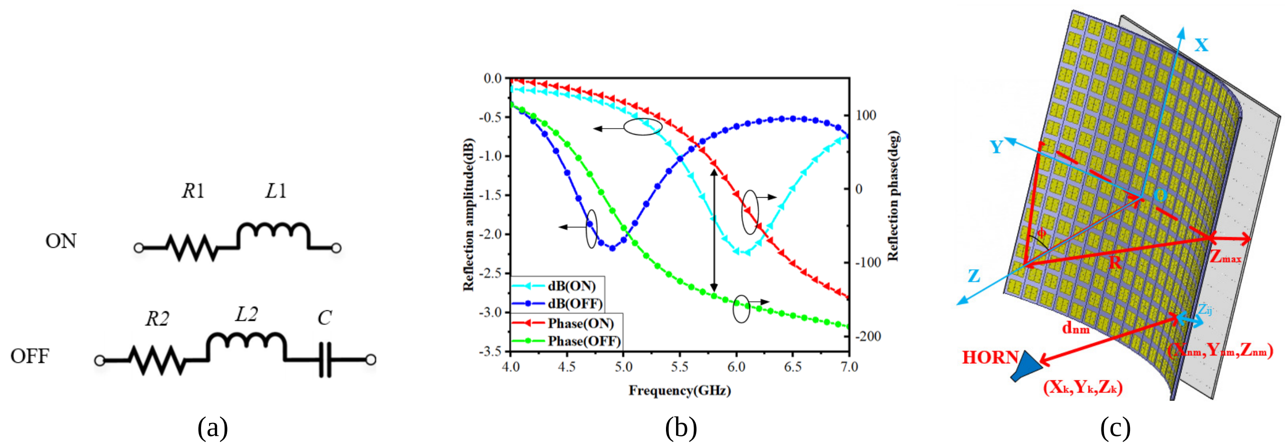

Figure 2. (a) Equivalent circuits for the ON/OFF state of the PIN diode. (b) Simulated reflection coefficients of the proposed RRA element. (c) Configuration of cylindrical reflectarray antenna.

3. CRRA ARRAY DESIGN

To verify the performances of the proposed conformal reconfigurable reflectarray antenna, we fabricated and measured a prototype of cylindrical CRRA with 16×18 elements, as shown in Figure 3(a). The dimension of fabricated prototype is $424.8\,\text{mm} \times 424\,\text{mm} \times 64.6\,\text{mm}$. A standard horn antenna is used as the feed source. The center of feed horn is parallel with the lower edge of the conformal array, and

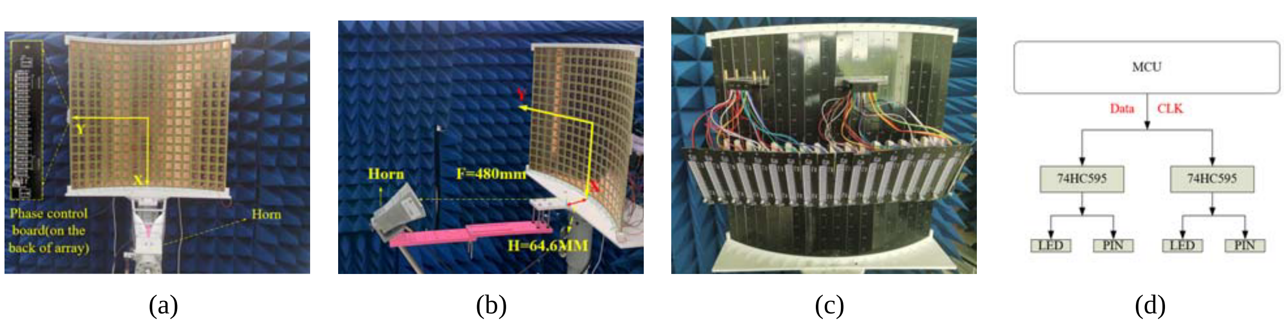

Figure 3. (a) Front view and (b) side view of the reflectarray antenna. (c) The backside of the reflectarray antenna. (d) Schematic diagram of bias network.

the distance from the center of feed horn to that of the lower edge of the conformal array is 480 mm, as shown in Figure 3(b). In this configuration, a 30° Y-polarized incident wave can illuminate the CRRA. The focal-diameter ratio of the horn to the array is 0.97.

The back of the reflectarray antenna is shown in Figure 3(c). The biasing network consists of 18 independent control boards. Each control board can independently adjust the ON/OFF state of the PIN diodes loaded in each column of reflectarray elements, thereby controlling the reflection phase shift of the reflectarray unit cells. In addition, according to the data sheet of SMP1340-040LF, the turn-on voltage of the PIN diode is $0.5 \sim 0.8$ V. Therefore, the control board we designed can generate the bias voltage of 0.8 V/0 V to control the ON/OFF of the PIN diode. Each control board can independently control each element in one column of reflectarray and uses two 51 single-chip microcomputers as a micro-control system to provide the required bias voltages. Finally, in order to check and debug the working status of the PIN diode, a suitable resistor and LED are connected in parallel to the shift register to display the working statuses of the PIN diodes visually. The schematic diagram of the control board is shown in Figure 3(d).

As shown in Figure 2(c), to generate the desired steering beam with the direction of (θ, ϕ), the required phase compensation for the nmth element on the reflectarray Φ_{nm} can be expressed as:

$$\phi_{nm} = k_0(d_{nm} + z_{nm} - (x_n \cos\varphi + y_m \sin\varphi)\sin\theta) \tag{1}$$

where k_0 is the wave number in free space, d_{nm} the distance from the feed horn to the nmth element, z_{nm} the compensation distance to the same plane in the antenna array, $Z_{\max}$ the maximum vertical distance of the cylindrical conformal antenna, and Z_{ij} the z coordinate of each unit. Next, we can quantize the required reflection phase compensation by the following scheme:

$$\phi_{nmq} = \begin{cases} 0^\circ & -235^\circ \le \phi_{nm} \le -55^\circ \\ 180^\circ & -55^\circ \le \phi_{nm} \le +125^\circ \end{cases} \tag{2}$$

where Φ_{nmq} indicates the quantized phase of the reflectarray unit cell.

4. PERFORMANCE ANALYSIS

The required phase compensation for different beam deflections can be obtained by controlling the input voltage of each PIN diode in the reflectarray element. The radiation patterns of the conformal reflectarray antenna prototype were measured in an anechoic chamber. The measured radiation patterns at 5.8 GHz are shown in Figure 4(a). It can be seen that the scanning angle range of the main beam can reach ±40° in YOZ plane. As the beam scanning angle increases, the gain decreases, and the waveforms also distort gradually. In addition, cross-polarization performances of the simulation and measurement are demonstrated in Figure 4(b). The results show that the measured cross-polarization level is 29 dB lower than the co-polarization level. The measured gain is 20.5 dBi, and the aperture efficiency is 16.918%.

Since the typical quantization loss of the 1 bit RRA is 3 dB [17], the theoretical aperture efficiency of the CRRA can reach 33.756%. Figure 4(c) shows the gain curves for different beam scanning angles.

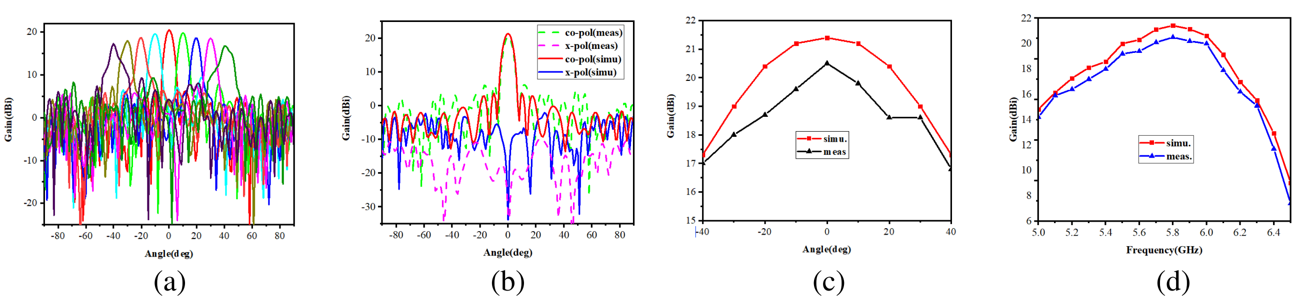

Figure 4. (a) Measured scanned beams in YOZ plane. (b) Radiation patterns of normal beam. (c) Gain point diagram for different scanning angles. (d) Simulated and measured gain bandwidth plots.

Figure 4(d) shows the gain bandwidth of the designed CRRA. We can see that the measured gains agree well with the simulated ones. The measured 1 dB gain bandwidth is 6.897%, and the 3 dB bandwidth is 13.793%. Finally, as shown in the comparison of Table 1, the cylindrical conformal reconfigurable reflectarray antenna designed in this paper can achieve ±40° beam scanning and has a good 1-dB gain bandwidth. The proposed CRRA has advantages of high gain and low cost. However, the proposed CRRA has low aperture efficiency and limited scanning angle range which can be attributed to the conformal and the phase errors generated during measurement. This design can provide a reference for the conformal applications of reconfigurable reflectarray antennas in the future.

Table 1. Performances comparison.

Ref	Frequency (GHz)	Type of control	Cell phase range	Aperture efficiency (%)	1-dB bandwidth (%)	Scanning Range (deg)
[8]	11.1/14.3	PIN	180	21.6/18.6	4.5/6.2	±60°/ ± 40°
[13]	11	Varactor	318	-	9	±40°
[14]	5.4	Varactor	360	-	-	±40°
[18]	26.5	MEMS	-	-	-	±40°
[19]	5	PIN	200	15.26	8.5	±50°
[20]	12.5	PIN	180	17.9	6	±50°
This Work	**5.8**	**PIN**	**180**	**16.9**	**6.9**	**±40°**

5. CONCLUSION

In this paper, 1-bit reflection phase shift with phase difference of 180° is obtained by loading PIN diode in a reflectarray element. By independently controlling the state of each PIN diode on the reflectarray, the required phase distribution for generating steering beam can be generated using phase quantization. Simulation and measurement both verify that the proposed CRRA can effectively generate scanning beams in the angle range of ±40°. The measured gain of the CRRA is 20.5 dBi with the aperture efficiency of 16.918%. The proposed CRRA can provide references for satellite and wireless communication systems with conformal requirements.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China under Grant No. 61961006 and the Science and Technology Foundation of Guizhou Province under Grant No. QKHJC[2020]1Y256.

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