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Design of Height-Adjustable Mechanically Reconfigurable Reflectarray

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Abstract—This paper presents a mechanically reconfigurable reflectarray with height adjustment for phase compensation. We designed, fabricated, and measured a prototype of 11×11 elements with microcontrollers to verify the feasibility of the proposed reflectarray. Simulated results show that the phase curve of the unit has good linearity and exhibit broadband characteristics. The maximum phase shift of the unit reaches about 200° at a center frequency of 16 GHz, which meets the requirement of a reflectarray with 1-bit phase quantization. Experimental results show that the gain of the proposed reflectarray is 17.7 dBi, with beam scanning range of $\pm 50^\circ$. The proposed configurations can be used for a low-cost beam scanning antenna in wireless communication.

1. INTRODUCTION

Reflectarray antenna usually consists of a feed antenna and reflective units, which can offer a preset aperture distribution to form designated beams [1]. Specially, reconfigurable reflectarray antennas (RRAs) have attracted widespread attention in applications such as wireless communications and radars, due to their properties of flexible beam steering. By adjusting the reflecting amplitude and phase response of each unit, beam steering can be flexibly realized. At present, RRAs usually realize beam steering by loading PIN diodes or varactor diodes in microstrip elements for reconfigurable phase compensation [2]. Since RRAs usually need extra bias networks for diodes, they are easily influenced by the induced current. Limited by the resonant feature of diodes loaded reflectarray element, RRAs also usually suffer from the problem of narrow bandwidth. Hence, increasing the bandwidth of RRAs has become a research hotspot in recent years. Several methods for broadband RRA design have been proposed. In [3], a 1-bit phase quantization method with PIN diode is used to compensate the phase and increase the bandwidth of a reconfigurable reflectarray antenna. Ref. [4] proposes a novel phase line for dynamic broadband tuning of active aperture coupled reflectarray elements. The RRAs integrated by PIN or varactor diodes to realize phase-shift compensation can be attributed to electronic control type, which still show relative narrow bandwidth. Mechanically reconfigurable reflectarrays can overcome this problem with good stabilities.

In this paper, we present a mechanically reconfigurable reflectarray. The required phase compensations are adjusted by the different heights of each reflectarray element. The reflectarray element adopts a non-resonant structure without active components, which not only dramatically improves the bandwidth but also reduces the loss.

2. THE BROADBAND REFLECTIVE ELEMENT

The reflective element can be viewed as the non-resonant type, as shown in Fig. 1. It consists of a metallic patch on the top, an FR4 substrate as the support structure, and polylactic acid (PLA)

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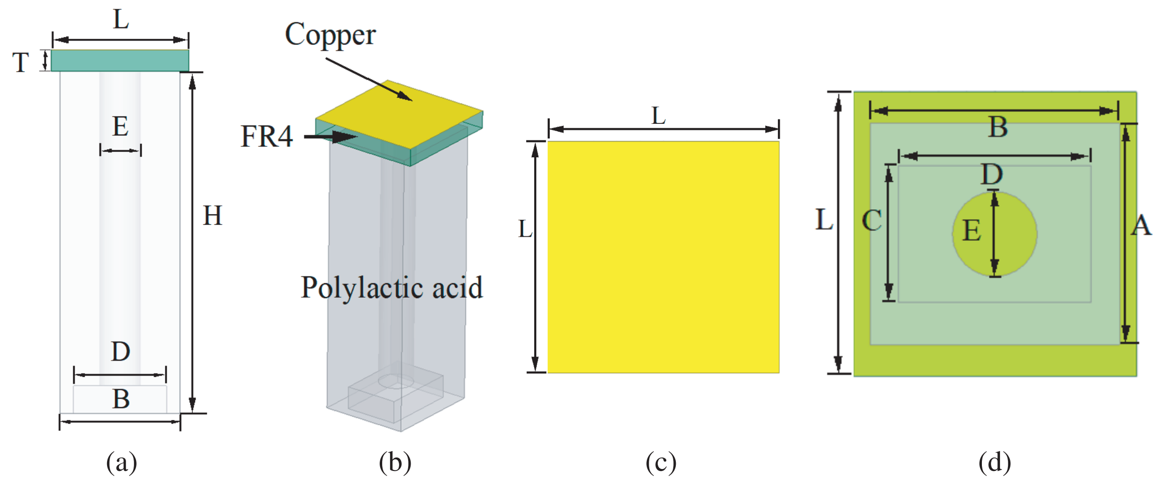


Figure 1. Unit overall structure diagram. (a) Front view. (b) Front view and side view. (c) Top view. (d) Bottom view. ($A = 7.8\,\text{mm}$, $B = 8.8\,\text{mm}$, $C = 4.8\,\text{mm}$, $D = 6\,\text{mm}$, $E = 3\,\text{mm}$, $L = 10\,\text{mm}$, $T = 1.6\,\text{mm}$).

material for the connection structure. The size of the metallic patch is $10\,\text{mm} \times 10\,\text{mm}$, and the working frequency is 16 GHz. The dimension of the FR4 dielectric support structure is $10\,\text{mm} \times 10\,\text{mm} \times 1.6\,\text{mm}$. The PLA connection structure is a cuboid with a hollow cylinder in the middle. It connects the stepper motor and reflective unit cell and facilitates the rotation of the stepper motor screw. There is a hollow cuboid under the PLA connection structure, which is used to place the sliding piece of the stepper motor screw rod. It can allow the stepper motor to drive the PLA connection structure to rotate. Then we need to use a blocking structure to make the reflective unit cell on the top move up and down. The PLA connection structure only plays the role of support and connection, and has little influence on the performances of the reflective element.

The reflective phase shift can be obtained by adjusting the height of the unit cell, which means that different heights correspond to different wave-path differences. Thus, different reflective phase-shifts can be obtained. The reflective phase and amplitude responses can be obtained by full-wave simulation by Ansys HFSS. The reflection phase and amplitude of the height-tunable RRA element are simulated, as shown in Fig. 2. Due to the wave path difference principle, the reflective phase-shift performance

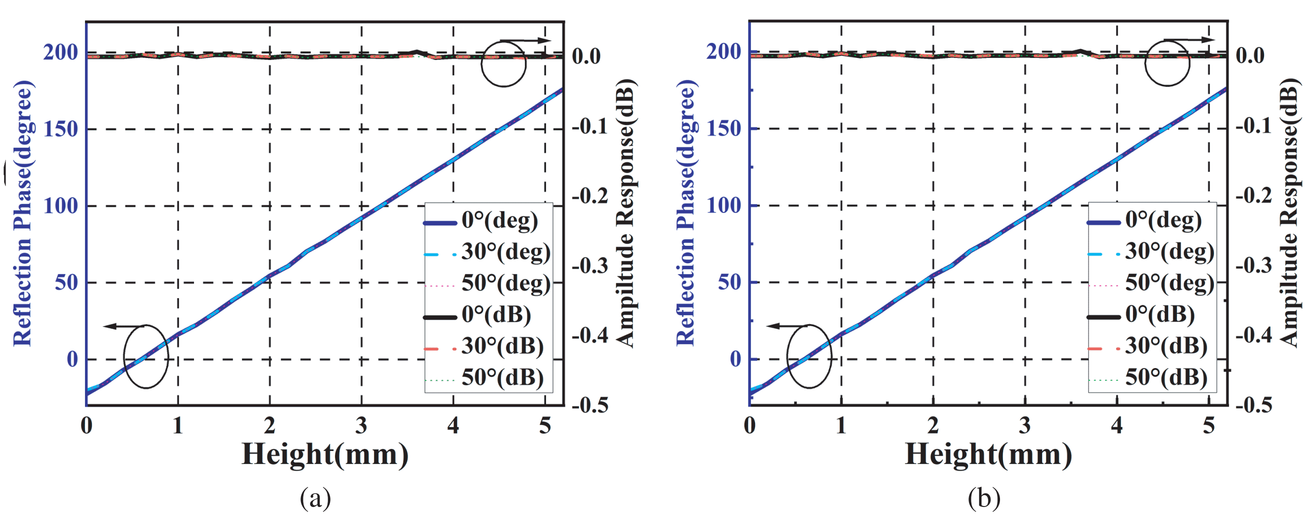
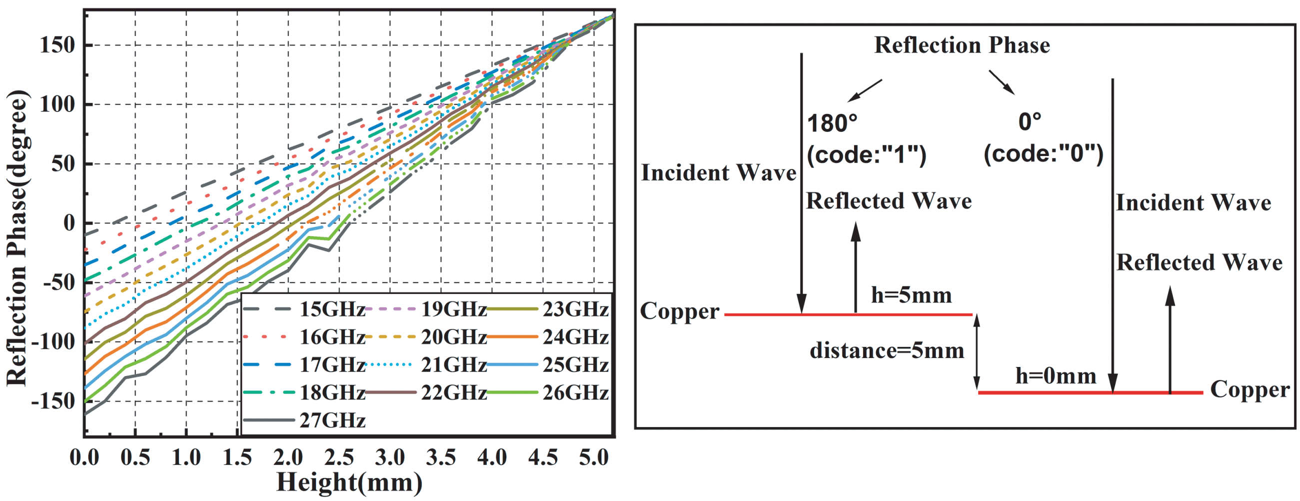


Figure 2. Simulated results of reflection phase and magnitude when incident angle varies from 0° to 50° at 16 GHz with (a) TM and (b) TE polarizations.

becomes more significant as the operating frequency increases. Considering that the size of the stepper motor is fixed, at the same time, the beam must be able to deflect at a large angle, we choose the working frequency as 16 GHz. At 16 GHz, the maximum phase shift can reach 200°, hence, we can use 1-bit quantification. In addition, the reflective loss of the element remains less than 0.1 dB within the variation range of height. In addition, Fig. 2 also shows the reflection coefficients of the element under oblique incident angles with TE and TM polarizations. We can see that the height-tunable RRA element owns good angle and polarization stabilities. Furthermore, the reflection phase curves of the element under different frequencies are also given in Fig. 3(a). From the simulated results, we can see that the reflective phase variation is linear according to both frequency and height, indicating that the proposed reflective element owns broadband characteristics.



(a) (b)

Figure 3. (a) Phase diagram at different frequencies. (b) Illustration of height controlling mechanisms and coding.

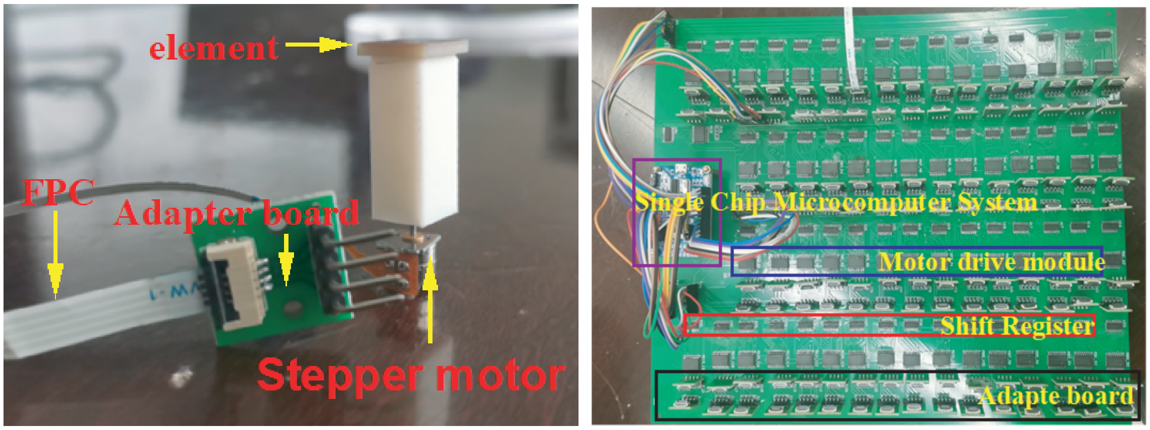
3. RRA DESIGN

To verify the performances of the reflective element, an array with 11 × 11 elements is designed to generate the high-gain beam. Due to the different distances from the feed to each unit, the path delays need to be compensated when the feed horn irradiates the reflectarray. The compensated phase shift for each reflectarray element consists of two parts: the path delay of a feed horn antenna and required phase shift for beam deflection. To launch an arbitrary high-gain beam directing at (θ_0, φ_0), the compensated phase-shift for each reflective unit cell can be expressed as [5]:

$$\Theta = k_0(d_i - (x_i \cos\varphi_0 + y_i \sin\theta_0)) \tag{1}$$

where Θ is the compensated phase required for each unit cell. $k_0 = 2\pi/\lambda$ represents the wave number in vacuum. λ is the wavelength at the working frequency. d_i indicates the distance from each element position of the array to the feed. In general, a k-bit RRA ideally has $2k$ tunable discrete phase states with a phase resolution of $360°/2k$. According to the analysis above, the reflection phase varies in direct proportion to the element's height. The reflection phases of 0° and 180° can be obtained when heights are 0 mm and 5 mm which is shown in Fig. 3(b), respectively.

The physical schematic of the connection between the unit and stepper motor is shown in Fig. 4(a). The stepper motor is connected to the control board through the FPC and adapter board to form a complete working system. Under this condition, the control board is designed, as shown in Fig. 4(b). It is composed of the smallest single-chip microcomputer system, shift register, and drive module. Firstly, to generate the desired high-gain beam, we can calculate the required phase-shift value for each unit cell. Then performing phase quantization and using the relationship between quantized phase and



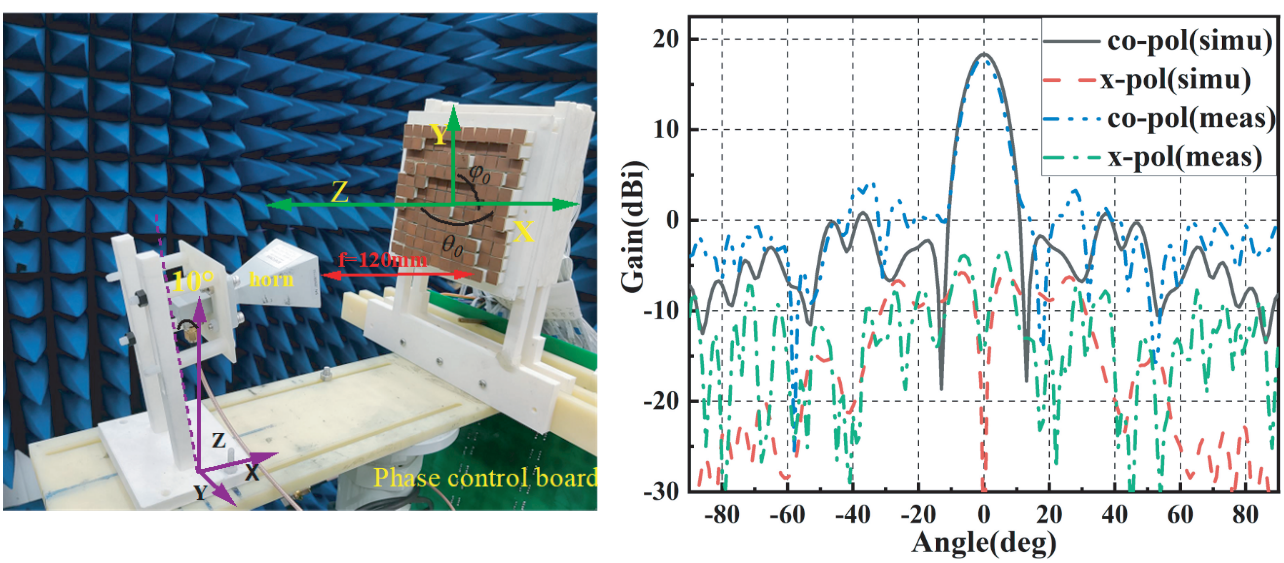
(a) (b)

Figure 4. (a) Physical connection schematic. (b) Phase control board.

a corresponding height of reflective element, the required rising height of the radiating unit at each position can be obtained.

4. RESULTS

A prototype of height adjustable reconfigurable reflectarray with 11×11 elements was designed, fabricated, and measured as shown in Fig. 5(a). The aperture size is 110 mm × 110 mm. A horn is used as the primary feed to generate y-polarized incident waves of 10°. The F/D ratio is 1.09. Using the height-tunable reflectarray, a normal high-gain beam is generated at 16 GHz. Fig. 5(b) compares the measured and simulated radiation patterns. The two results agree well, and they both show that the proposed reflectarray can effectively generate a high-gain beam in a normal direction. In addition, the measured gain is 17.7 dBi. Furthermore, both the simulated and measured cross-polarization levels are less than 24 dB. The calculated aperture efficiency is about 14.28%.



(a) (b)

Figure 5. (a) Measurement setup. (b) Comparison of simulated (simu) and measured (meas) radiation patterns of $\theta = 0°$ at 16.0 GHz.

The measured radiation patterns of scanning beams from $\theta = 0°$ to $\theta = 50°$ in the YOZ plane are plotted in Fig. 6(a), which are normalized to the measured gain of 17.7 dBi at $\theta = 0°$. We can see that the scanning beams in the range from $\theta = 0°$ to $\theta = 50°$ can be effectively generated by the proposed height-tunable RRA. In addition, the measured gain at $\theta = 50°$ is 14.3 dBi which means that the gain variation of the RRA within $\theta = 50°$ is only 3.4 dB. The low aperture efficiency of 14.28% is mainly affected by the following two factors. Firstly, quantization phase errors are big since there are only two phase-shift values of the reflectarray element. Second, the practical measured environment and installation of reflectarray antenna can also cause losses in gain. Furthermore, the gain bandwidth of the RRA in the boresight direction was also investigated. Measured results are compared with simulated one in Fig. 6(b). The measured −3 dB gain bandwidth is from 14.87 to 21.11 GHz with 39% relative bandwidth. This indicates that the height-tunable RRA can effectively generate high-gain beams over a relatively wide bandwidth. The comparison with several representative RRA designs is summarized in Table 1. We can see that the proposed height-tunable RRA owns the widest operational bandwidth.

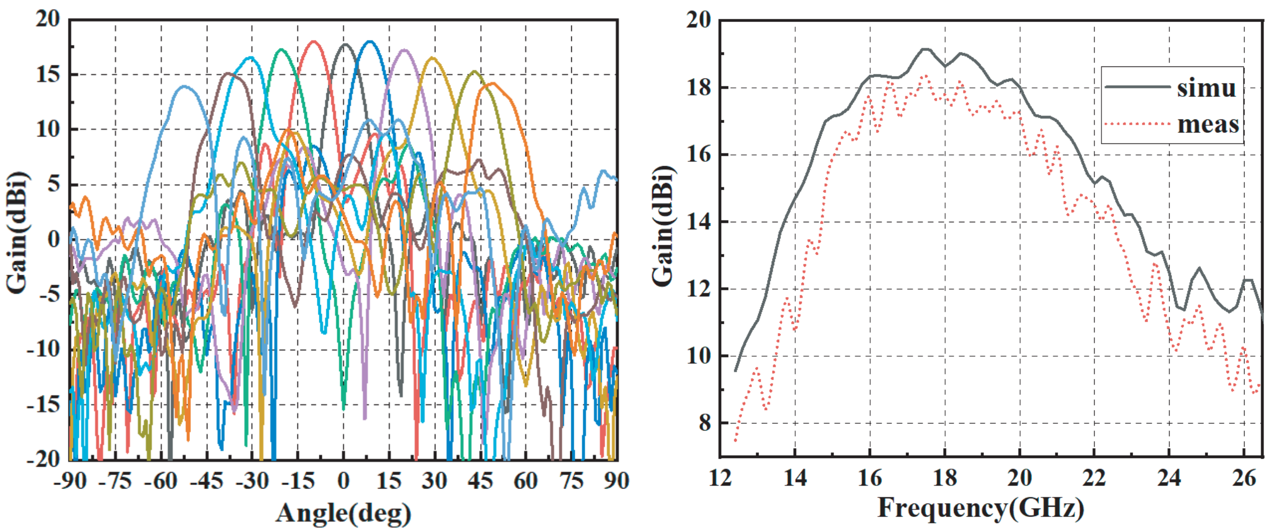


Figure 6. (a) Measured scanning beams within ±50° in the YOZ plane at 16.0 GHz. (b) Gain bandwidth comparison between simulation and measurement.

Table 1. Comparison of some existing works.

Ref.	Frequency (GHz)	Phase control method	Phase shift	Aperture efficiency (%)	−1 dB	−3 dB	SR
[3]	5	PIN	200°	15.26	8.4	-	±50°
[6]	10.5	Unit of size	430°	40	23	29	NA
[7]	12.6/14.25	PIN	180°	27.1/22.2	-	11.6/11.9	±60°
[8]	4.8	Height	324°	48.6	6.2	-	±60°
[9]	8	Varactor diode	360°	51.8	-	28.6	±60°
[10]	5.4	Varactor diode	373°	-	-	3.6	±40°
[11]	11	Height	318°	18.3	10	-	±50°
This work	16	Height	200°	14.28	-	39	±50°
−1 dB: −1 dB bandwidth (%). −3 dB: −3 dB bandwidth (%). SR: Scanning Range (deg)							

5. CONCLUSION

A 1-bit broadband reconfigurable reflectarray based on height-tunable control is designed, manufactured, and measured in this paper. In order to realize the height as a factor of phase compensation, a phase control board of a single-chip microcomputer was employed to adjust the height of the unit. Experiment verifies the validity of our design. Simulations and experiments show that the proposed 1-bit height mechanically reconfigurable reflectarray is of broadband performance. Beam steering of $\pm 50^\circ$ was realized, and the -3 dB bandwidth is 39%. Measurement results are in good agreement with the theoretical design and simulation ones, which verify that the proposed RRA has good beam steering capabilities and flexible radiation performance.

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