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RESEARCH ARTICLE

Hybrid Reflectarray Antenna of Passive and Active Unit Cells for Highly Directive Two-Direction Beam Steering

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ABSTRACT A hybrid reflectarray antenna (RA) composed of passive and active unit cells that can steer a beam into two selected directions with high aperture efficiencies is designed and experimentally verified. The hybrid RA is implemented by a combination of one-bit active and passive unit cells, which enables the quantization of phase profiles of the reflection coefficients on the antenna surface to 120°. This combination can improve the quantization efficiency of the conventional one-bit reconfigurable RA quantized with 180°. A combination of the passive unit cells of which the phases of reflection coefficients are 180° is determined to be included simultaneously in two quantized phase profiles for two-direction beam steering. As a proof of concept, the hybrid RA operating at 10.1 GHz is designed to steer the beam to the vertical angles θ of −18° and 18° on the E-plane. By comparing them with those of the one-bit RA, we confirmed that the aperture efficiencies are improved by 41.85% and 69.41% in simulations and by 37.19% and 60.19% in measurements for the vertical angles θ of −18° and 18°, respectively.

INDEX TERMS Hybrid reflectarray, PIN diode, three states, quantization efficiency, aperture efficiency.

I. INTRODUCTION

Reconfigurable reflectarray antennas (RA) are beamforming antennas that can steer the main beam into multiple directions. They have attracted much attention because of their various applications, such as their use for base stations of wireless communications, sensor networks of the internet of things, and microwave wireless power transfers [1], [2], [3]. To attain commercialization, different kinds of RAs have been reported to simplify and reduce the costs of electronic control systems.

As one of the candidates for simplified RAs, one-bit RAs utilizing PIN diodes have been proposed [4], [5], [6], [7]. PIN diode-based RAs have great advantages from the perspective of switching the speed, size, and cost of the system. However, they have the inherent limitation of relatively low aperture efficiency, owing to the one-bit quantization of phase profiles of the reflection coefficients on the antenna surface, which accompanies a loss of 3 dB [8]. As an alternative, two-bit RAs have been proposed [9]. Even though the quantization loss could be improved by utilizing the two-bit control, there exists a critical issue that the complexity of the bias network has to be increased. It may increase the numbers of layers and via holes of reflectarray, and may cause side effects such as coupling between bias lines with the radiating patch.

In this study, a hybrid RA composed of passive and active unit cells is proposed for two-direction beam steering with high aperture efficiencies based on a simple one-bit control. The hybrid reflectarray is designed by combining one-bit active and passive unit cells to enable the quantization of the phase profiles with 120°. The dimensions of a copper-square ring of the one-bit active unit cell are optimized by the genetic

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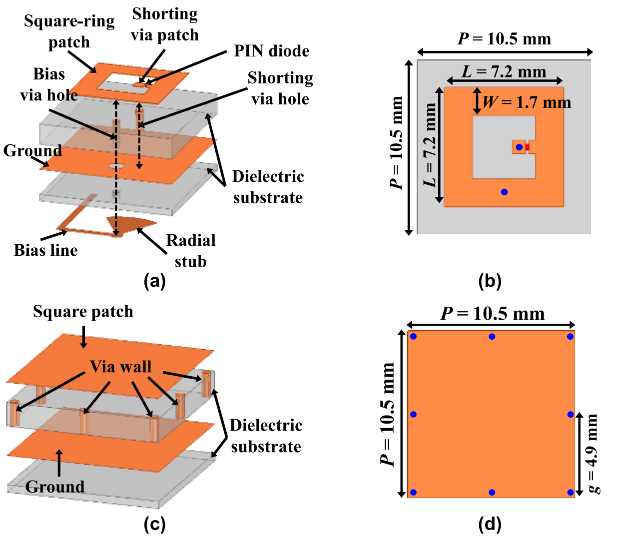

FIGURE 1. **Schematics of proposed unit cells. (a) Three-dimensional and (b) Top views of one-bit active unit cell. (c) Three-dimensional and (d) top views of passive unit cell.**

algorithm (GA) [10] to match its phases of the reflection coefficients of 60° or −60° to the on or off states of the PIN diode. In addition, the passive unit cell is designed by connecting a square patch to the ground through via holes to match the phase of the reflection coefficient to exactly 180°. As a proof of concept, a hybrid is implemented and experimentally verified, which can steer a beam in two directions: the vertical angles θ of −18° and 18° on the E-plane. By comparing its measured aperture efficiencies with those of a one-bit RA [7], the effectiveness of the proposed scheme is verified.

II. DESIGN

A. DESIGN OF UNIT CELLS

To design the hybrid reflectarray composed of the active and passive unit cells, which enables the quantization of the phase profiles to 120°, we design a one-bit active unit cell with the phases of the reflection coefficients at 60° or −60° for the on or off states of the PIN diode. The phases are determined, assuming that the phase of the reflection coefficient of the passive unit cell is 180°. Figures 1(a) and 1(b) show schematics of the one-bit active unit cell with detailed descriptions and dimensions of the structure, respectively, of which the periodicity P is 10.5 mm (0.35 λ_0). The unit cell consists of two Taconic TLY-5 ($\varepsilon_r = 2.2$, $\tan\delta = 0.0009$) dielectric substrates, of which the thicknesses are 1.575 and 0.508 mm for the top and bottom, respectively. The copper-square-ring patch combined with the PIN diode is located on the top layer, which reradiates the incident electromagnetic waves. Here, the model MACOM MA4GP907 is chosen for the PIN diode, which stably operates in the X-band. One side of the PIN diode is connected to the ground through a via hole, whereas the other side is connected to the patch. To induce a bias voltage of 1.2 V in the PIN diode, we connect a bias line under the bottom layer to the ring patch through another via hole. A radial stub is designed to block leakage of the radio-frequency current through the bias line.

The dimensions of the ring patch are determined optimally by adopting GA [10], utilizing the periodic boundary condition in ANSYS HFSS at 10.1 GHz. For optimization, the ranges of the dimensions L and W in Fig. 1 are set to 0.1 mm $\leq L \leq$ 10 mm, 0.1 mm $\leq W \leq$ 4 mm, and 2 mm $\leq L - 2W$. The last condition is set to guarantee sufficient space for a combination of the PIN diode. For the on state, the PIN diode is modeled as a series circuit of a resistor and an inductor, of which the resistance and inductance are 4.2 Ω and 0.05 nH, respectively. For the off state, the PIN diode is modeled as a parallel circuit of a resistor and a capacitor, of which the resistance and capacitance are 300 kΩ and 50 fF, respectively.

Based on the full-wave simulation, the figure of merit (FOM) of GA is calculated as (1), shown at the bottom of the page, where $\angle S_{11,off}$ and $\angle S_{11,on}$ indicate the phases of the reflection coefficients for on and off states, respectively. The iteration of GA is repeated six times until two dominant genes exactly coincide with each other owing to a sufficient convergence of the algorithm [10]. As a result, L and W are optimized to 7.2 mm (0.24λ_0) and 1.7 mm (0.06λ_0), respectively. When the optimal dimensions are used, the magnitude and phase of the reflection coefficient are −0.2 dB and 57.16° for the on-state and −0.2 dB and −68.58° for the off-state, respectively.

A schematic of the passive unit cell is shown in Fig. 1 (c), (d). The size of the square patch is determined to be the same as the size of the unit cell P. For perfect reflection at the top of the square patch, via holes are added. In addition to the connection between the patch and the ground, the configuration prevents leakage of the incident power into the gap between the square patch and the ground plane. The optimal number and spacing between via holes are determined to guarantee the maximum aperture efficiencies of the hybrid in two directions, which is treated in the next paragraph. We confirm that three via holes per each side of the unit cell with a distance of 4.9 mm (0.15 λ_0) between the neighbor via holes are sufficient. The simulated results of the proposed active and passive unit cells are summarized in Fig. 2 and Table 1. Figure 2 shows reflection coefficients of the active and passive unit cells for the frequency, and Table 1 shows the magnitudes and phases of the reflection coefficients of them at 10.1 GHz.

$$\mathrm{FOM} = \frac{1}{2}\left(\frac{\left|60^\circ - \angle S_{11,on,10.1\mathrm{GHz}}\right|}{60^\circ} + \frac{\left|120^\circ - (\angle S_{11,on,10.1\mathrm{GHz}} - \angle S_{11,off,10.1\mathrm{GHz}})\right|}{120^\circ}\right), \tag{1}$$

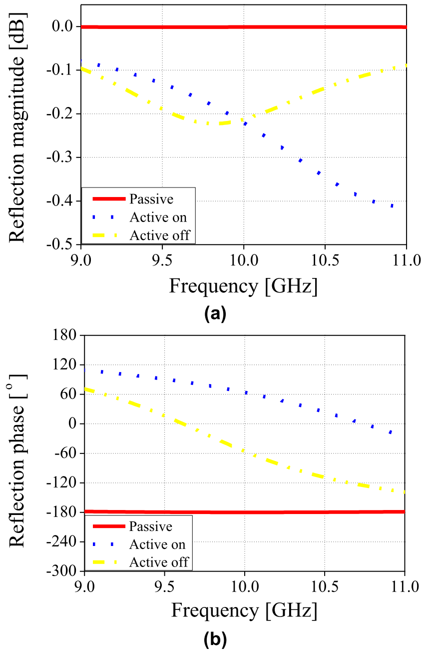

FIGURE 2. Reflection coefficients of the active and passive unit cells for the frequency. (a) Magnitudes and (b) Phases.

TABLE 1. Reflection coefficients of unit cells at 10.1 GHz.

Type	State	Magnitude [dB]	Phase [°]
One-bit active	On	-0.2	57.16
	Off	-0.2	-68.58
Passive	NA	0	180

B. HYBRID REFLECTARRAY

By manipulating the phase of the reflected wave on the surface of the antenna, the main beam can be steered into the intended direction [7]. To this end, the phase of the reflected wave steered into the specific direction is described as ϕ_{mn}^{output} on the surface of the antenna, where m and n are the indices of the unit cells in the x and y axes, respectively. If the phase of the incident wave on the surface is described as ϕ_{mn}^{input}, the required phase $\phi_{mn}^{required}$ that should be realized by the phase of the reflection coefficient of the unit cell can be calculated as follows:

$$\phi_{mn}^{required} = \phi_{mn}^{output} - \phi_{mn}^{input} + \phi^{ref.}, \tag{2}$$

where $\phi^{ref.}$ indicates a reference phase, which is a constant that can be arbitrarily determined because it does not affect the direction of the reflected wave. By contrast, the reference phase can affect the quantization efficiency because it determines how the continuous phase profile is quantized into three states of the unit cells, of which the phases are fixed to 60°, 180°, or −60°. The three states of the unit cells utilized for the quantization of the continuous phase profiles are summarized in Table 2.

As a proof of concept, the hybrid array composed of the active and passive unit cells is designed to steer the main beam into θ of −18° and 18° on the E-plane. Here, the minus and plus signs mean that the steering directions are oriented from $+z$ axis to $-x$ and $+x$ axes, respectively. First, two phase profiles $\phi_{mn}^{required}$ matched to the two directions are calculated using Eq. 2, as shown in the left and center columns of Fig. 3. Then, the combinations of the passive unit cells are determined to be included in both phase profiles simultaneously, as shown in the right column of Fig. 3. At this stage, the reference phase $\phi^{ref.}$ is swept from 0° to 350° with 10° intervals. To select the best combination of the passive unit cells, we calculate the quantization efficiency η_q of the hybrid reflectarray as follows:

TABLE 2. Three states of unit cells for 120° quantization.

Range of $\varphi_{mn}^{required}$	Quantized phase	Type	State
$0° \le \varphi_{mn}^{required} < 120°$	60°	Active	On
$120° \le \varphi_{mn}^{required} < 240°$	180°	Passive	NA
$240° \le \varphi_{mn}^{required} < 360°$	-60°	Active	Off

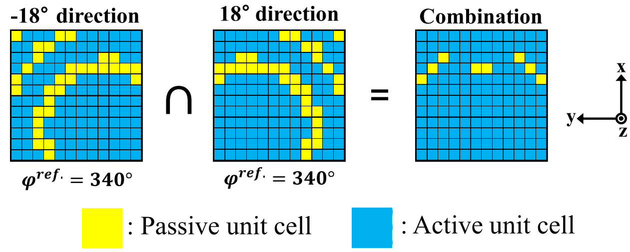

FIGURE 3. Optimal combination of passive and active unit cells for two-direction beam steering to θ of −18° and 18° on the E-plane.

$$\eta_q = \frac{\left|AF\left(\theta,\ \varphi\right)_{3-state}\right|^2}{\left|AF\left(\theta,\ \varphi\right)_{continuous}\right|^2}, \tag{3}$$

where $AF(\theta, \varphi)_{3-state}$ and $AF(\theta, \varphi)_{continuous}$ indicate the array factors calculated by the quantized and continuous phase profiles, respectively [7].

From the calculations of η_q by sweeping $\phi^{ref.}$ the maximum quantization efficiency of 52.23% is found with $\phi^{ref.} = 340°$, whereas the minimum one of 37.36% is confirmed with $\phi^{ref.} = 180°$. The results indicate that the reference phase $\phi^{ref.}$ is a dominant factor that determines the optimal combination of the hybrid reflectarray. Figs. 4(a) and 4(b) show the optimal combinations of two states of actively controllable unit cells mixed with passive ones for beam steering to θ of −18° and 18°, respectively, determined by $\phi^{ref.} = 340°$.

To confirm the merit of the hybrid three-states compared with the one-bit case, the quantization efficiencies of both cases are compared in Fig. 5. For beam steering to θ of −18° and 18°, we confirm that the maximum quantization efficiency of 52.23% of the hybrid three-states is 14.25% higher than that of the one-bit reflectarray (45.62%). By contrast, the quantization efficiencies of the hybrid reflectarray are lower than those of the one-bit case in the ranges of $10.2° \le |\theta| \le 21.9°$. This implies that the proposed scheme

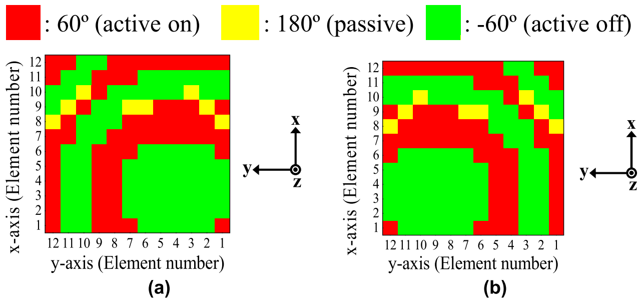

FIGURE 4. Optimal combinations of two states of actively controllable unit cells mixed with passive ones for beam steering to (a) θ of −18° and (b) 18° on the E-plane.

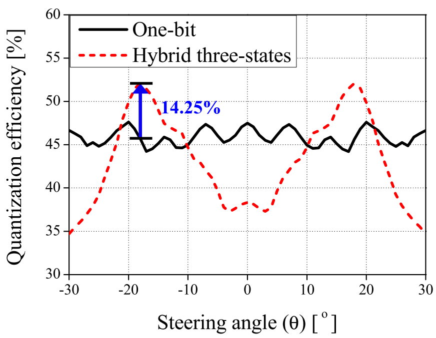

FIGURE 5. Quantization efficiencies of one-bit and hybrid three-states reflectarrays vs steering angle θ on the E-plane.

combining the active unit cell with the passive one is effective in the desired directions. The quantization efficiency of the one-bit reflectarray is optimized by changing the reference phase in the same manner.

III. RESULTS

To verify the enhancement of the aperture efficiency of the hybrid RA compared with that of the one-bit case [7], we simulate and measure two prototypes composed of 12 × 12 unit cells under the same conditions. Figure 6 shows the prototype of the hybrid RA. For the one-bit case, the same configuration is used, except for the combination of the unit cells. For instance, the sizes of both apertures are set to 126 × 126 mm^2, and the same feed horns of 11 dBi gain are adopted for both cases. The locations of the feed horns are determined to satisfy F/D of 0.36 and offset angle of −25° in the xoz plane, where F and D indicate the feeding distance and the aperture size, respectively. Therefore, the spillover and illumination efficiencies are equally calculated as 82.1 and 83.5%, respectively, for the two cases. The product of them is 68.6%.

To improve the accuracy of the measurements, we attach microwave absorbers around the prototypes to minimize undesired reflections from the acrylic jig. Especially for the proposed hybrid reflectarray, the unit cells are assembled using two modules composed of 6 × 12 unit cells, as shown in the inset of Fig. 6. The modules allow easy replacement of

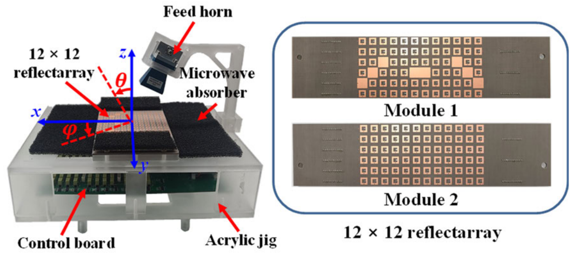

FIGURE 6. Prototype of hybrid RA.

the damaged active unit cell with the normal one. Because the active unit cells are controlled by utilizing one-bit sequence, the complexity of the bias network is the same with that of the conventional one-bit reflectarray. The radiation patterns of the prototypes are measured via an E8362B PNA network analyzer of Keysight inside an anechoic chamber, of which the receiving antenna is separated from the sample by 7 m.

The aperture efficiencies of the fabricated prototypes are calculated as follows [11]:

$$\eta_a = \frac{G_{mea.}}{G_{\max}} = \frac{G_{mea.}}{\frac{4\pi A}{\lambda^2}\cos\theta}, \tag{4}$$

where the measured gain, maximum gain, aperture area, and steering angle are indicated by $G_{mea.}$, $G_{\max}$, A, and θ, respectively.

The simulated and measured results of both prototypes are shown in Fig. 7 and summarized in Table 3. The simulated gains and aperture efficiencies of the hybrid RA are 17.52 dBi and 26.27% for θ of −18° and 17.96 dBi and 29.24% for θ of 18°, respectively. By comparing the simulated aperture efficiencies with those of the one-bit case, improvements of 41.85% and 69.41% are found for θ of −18° and 18°, respectively. The measured gains and aperture efficiencies are 16.60 dBi and 21.25% for θ of −18° and 16.64 dBi and 21.45% for θ of 18°, respectively. By comparing the measured aperture efficiencies with those of the one-bit case, improvements are confirmed as 37.19% and 60.19% for θ of −18° and 18°, respectively. The measured 1 dB-gain bandwidths of hybrid RA are confirmed as 570 and 610 MHz for θ of −18° and 18° as shown in Figs. 8(a) and 8(b), respectively. To clarify the bandwidth performances, the measured aperture efficiencies are supported in both cases. In addition, errors in the steering angles of the hybrid RA are effectively reduced compared with those found in the one-bit case, as summarized in Table 3.

While the maximum gains of the proposed hybrid RA are increased compared with those of the one-bit RA, the side lobe levels (SLLs) of the proposed one are also increased compared with those of the one-bit case. From the measurements, SLLs of the hybrid case are confirmed as −9.24 and −10.43 dB which are higher than those of the one-bit case −13.98 and −15.11 dB for θ of −18° and 18°, respectively. Although the proposed hybrid configuration improves

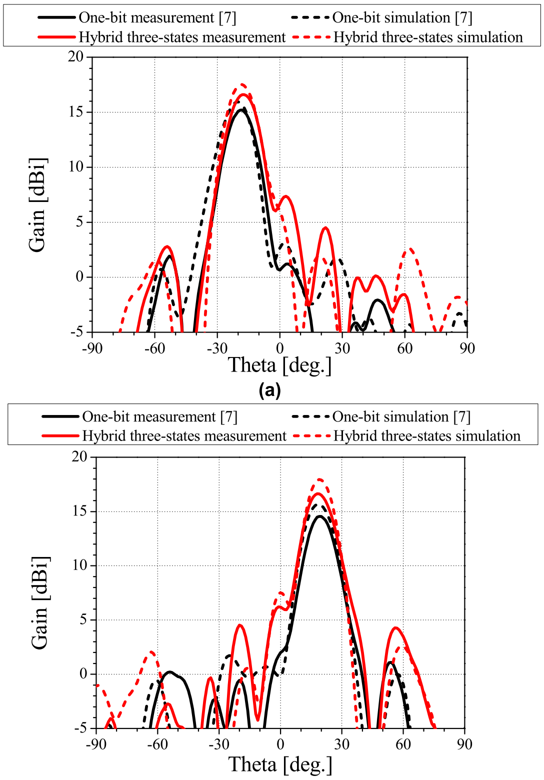

FIGURE 7. Radiation patterns of one-bit and hybrid three-states RAs at 10.1 GHz for (a) θ of $-18°$ and (b) θ of 18° on the E-plane.

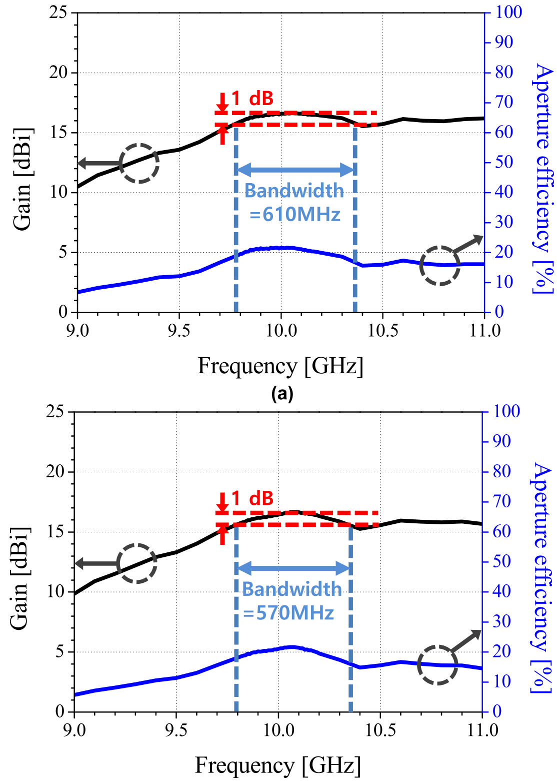

FIGURE 8. Measured gains and aperture efficiencies for (a) θ of $-18°$ and (b) θ of 18° on the E-plane.

TABLE 3. Comparisons of beam-steering performances between the conventional one-bit and proposed hybrid RAs.

Design	Scan angle θ	Direction error		Gain / Aperture efficiency	
		Simulated	Measured	Simulated	Measured
One bit [7]	-18°	-2°	-1°	15.95 dBi / 18.52%	15.20 dBi / 15.49%
	18°	1°	2°	15.67 dBi / 17.26%	14.54dBi / 13.39%
Hybrid	-18°	0°	0°	17.52 dBi / 26.27%	16.60 dBi / 21.25%
	18°	1°	0°	17.96 dBi / 29.24%	16.64 dBi / 21.45%

TABLE 4. Comparisons of RAs near one of the target angle θ of 18°.

	[5]	[6]	[7]	This work
Control type	One bit	One bit	One bit	Hybrid three-states
Frequency	5 GHz	15 GHz	10.1 GHz	10.1 GHz
Unit cell size	0.55 λ_0	0.475 λ_0	0.35 λ_0	0.35 λ_0
Number of elements	144 cells (12 × 12 square arrays)	208 cells (16 × 16 circular arrays)	144 cells (12 × 12 square arrays)	144 cells (12 × 12 Square arrays)
Aperture size	6.6 × 6.6 λ_0^2	7.6 × 7.6 λ_0^2	4.1 × 4.1 λ_0^2	4.1 × 4.1 λ_0^2
F/D (offset angle)	0.9 (0°)	1.03 (26°)	0.36 (25°)	0.36 (25°)
Peak gain (angle on the E-plane)	18.5 dBi (20°)	18.9 dBi (20°)	14.54 dBi (18°)	16.64 dBi (18°)
Aperture efficiency	14.47%	12.37%	13.39%	21.45%

the quantization efficiencies of the reflectarray for the two directive beam steering, it accompanies deteriorated SLLs owing to unintended mutual coupling among different types of the unit cells [12], [13].

To clearly show the advantage of the proposed hybrid RA, performances of the hybrid one and those of recently reported RAs are compared in Table 4. The references [5] and [6] provide beam steering performances near the one of the target angles θ of 18°. The reference [7] is the same with the conventional one-bit RA benchmarked in this work. Among the aperture efficiencies of the RAs near θ of $-18°$, the aperture efficiency of the proposed one indicates the highest value 23.45% that is 48.24% and 73.4% higher than those of references [5] and [6], respectively.

IV. CONCLUSION

A hybrid RA composed of passive and active unit cells that steers a beam into two-direction with high aperture efficiencies is proposed. To match the phases of the reflection coefficients of the one-bit active unit cell to 60° or $-60°$ for the on or off states of the PIN diode, the dimensions of the square-copper-ring patch are optimally designed utilizing GA. To achieve a phase of 180° for the passive unit cell, the square patch is connected to the ground plane through via holes. The combination of the passive unit cells is determined to be included in both of the two quantized phase profiles for the beam steering to θ of $-18°$ and 18° on the E-plane.

To maximize the aperture efficiencies in the two directions, we sweep the two phase profiles simultaneously by changing the reference phase from 0° to 350° at a 10° interval. Compared with the one-bit RA, the aperture efficiencies of the proposed hybrid RA are improved by 41.85% and 69.41% in simulations and by 37.19% and 60.19% in measurements for θ of $-18°$ and 18°, respectively. In addition, the errors in the steering angles of the hybrid RA are effectively reduced compared with those of the one-bit case. The proposed hybrid RA can be applied to improve the transmission efficiencies of sensor networks or wireless power transfers in limited ranges of steering angles.

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