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Fan Wu, Wu-Guang Zhao, Xiaoyue Xia, Jingxue Wang, Zhi Hao Jiang, et al.. A 2 bit Circularly Polarized Reconfigurable Reflectarray Using p-i-n-Diode-Tuned Crossed-Bowtie Patch Elements. IEEE Transactions on Antennas and Propagation, 2023, 71 (9), pp.7299-7309. 10.1109/TAP.2023.3291773 . hal-04244263

HAL Id: hal-04244263

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A 2-Bit Circularly-Polarized Reconfigurable Reflectarray Using PIN-Diode-Tuned Crossed-Bowtie Patch Elements

Fan Wu, *Member, IEEE*, Wu-Guang Zhao, Xiaoyue Xia, Jingxue Wang *Member, IEEE*, Zhi Hao Jiang, *Member, IEEE*, Ronan Sauleau, *Fellow, IEEE*, and Wei Hong, *Fellow, IEEE*

Abstract—A wideband, wide-scanning-angle and high-efficiency 2-bit circularly-polarized (CP) reconfigurable reflectarray is presented for two-dimensional (2D) dynamic beam control. The reflectarray is achieved using tunable elements based on crossed-bowtie patches with annually distributed PIN diode loadings. By squeezing two interlaced crossed-bowtie patches into a single unit cell and making them strongly coupled, doubled phase state and drastically extended element bandwidth are simultaneously obtained. In addition, simple biasing circuitry and low-loss reconfigurable mechanism are also introduced. The fabricated 16×16 two-dimensional beam-scanning reflectarray working at X-band demonstrates experimentally a 3-dB gain and axial ratio bandwidth of 22%, a peak gain of 24.5 dBic, an aperture efficiency of 35%, sidelobe levels of around -20 dB and a scanning range up to $\pm 60^\circ$. With such well-rounded performances, the proposed reflectarray design, which realizes 2D CP beam scanning, can be a competitive candidate for space and satellite communications.

Index Terms—Beam scanning, circular polarization, high-gain antenna, PIN diode, reconfigurable antenna, reflectarray, transmitarray.

I. INTRODUCTION

HIGH-gain antenna with dynamic beam control offers a great flexibility for many modern wireless communication and sensing systems [1]. Meanwhile, achieving circularly-polarized (CP) radiation for the steerable pencil beams is very attractive in practice due to the potential benefits that a CP wave brings about especially when the wireless channel becomes unpredictable [2].

Reconfigurable CP beam can be launched using traditional

high-gain antennas such as parabolic reflectors and the phased arrays through mature methodologies. However, these solutions often suffer from their own drawbacks including bulky size and increased costs. Reflectarray antennas combine advantages from both the parabolic reflector and the phased array, possessing a spatial feeding configuration, a planar radiating surface as well as flexible wave front manipulation [3, 4]. By incorporating tunable devices or materials into its unit-cell, dynamically controllable beams can be obtained in a cost-effective way [5, 6]. Among many of the approaches implemented to realize electronically reconfigurable reflectarrays (RRAs), the use of PIN diodes has attracted the most research attentions because of its advantages such as low cost, simplicity and the off-the-shelf availability. As revealed in [7], a classical way to alter the resonance and hence the reflection phase of a microstrip patch reflectarray element consists in grounding the patch via a diode-controlled shorting pin at its radiating edge. Through switching the state of the PIN diode, the resonant frequency of the patch fundamental mode can be shifted and the phase value of the back-scattered field can be reversed, resulting in an one-bit phase adjustment. This idea has been further exploited and applied to enable numerous reconfigurable designs that realize single-band or dual-band operation with linear or dual-linear polarizations [8-16].

However, the realization of RRA can become quite challenging when it comes to manipulate electronically a CP beam. The design of reconfigurable CP reflectarrays [17-19] based on PIN diodes mainly follow the idea of element rotation method originally proposed by Huang [20]. In these designs, two orthogonal polarizations should be properly perturbed by switching the states of the diodes and a radial symmetry is established in the element configuration. As a result, the element bandwidth shrinks and complexity of the unit-cell increases. In particular, for reconfigurable designs that intend to realize multiple CP states (i.e., finer than 1-bit phase resolution), more diodes with independent control are needed. The resultant complex unit-cell would further impose difficulty in the practical implementation of the CP RRA, as indicated by the reported multi-bit CP RRA element designs [21, 22].

To date, three approaches have been found in the literature to achieve a fully reconfigurable CP reflectarray. Methods using PIN diodes [17, 19] and motors [18] are adopted to realize the desired element rotation in either an electrical or a mechanical

Manuscript received XXXX. This work was supported in part by the National Natural Science Foundation of China under Grants 62101175, 62122019 and 62293492, in part by the Natural Science Foundation of Jiangsu Province under Grant BK20200506 and in part by the Hong Kong Scholars Program under Grant XJ2021016 (Corresponding author: *Zhi Hao Jiang*).

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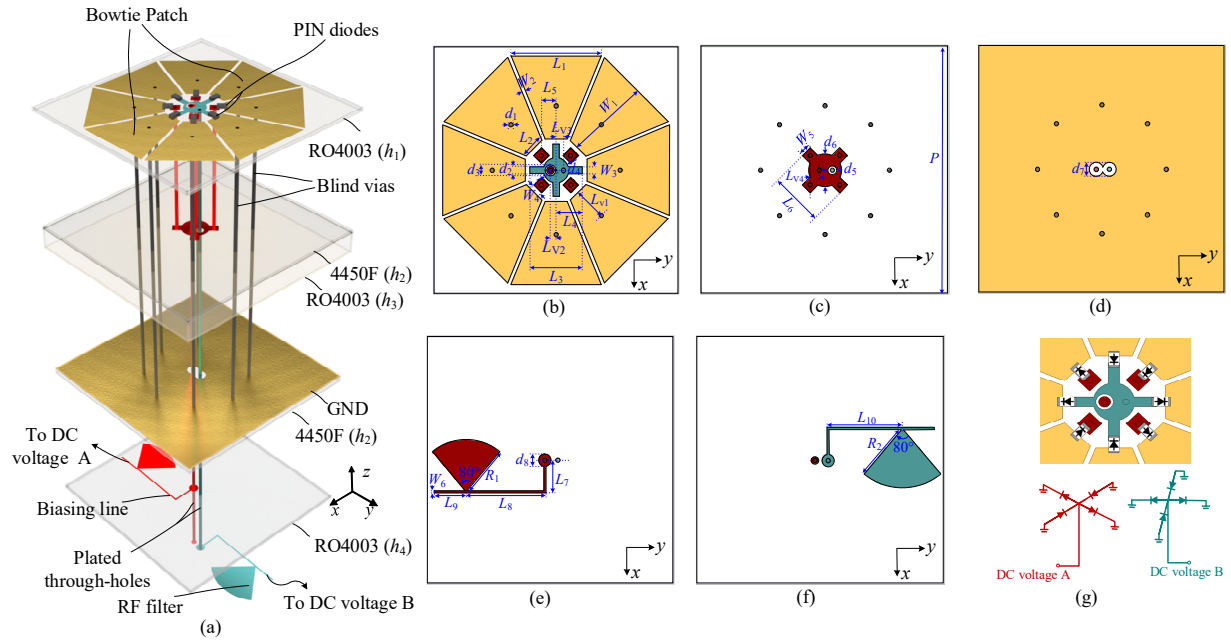


Fig. 1. Configuration of the proposed 2-bit reconfigurable CP reflectarray unit-cell: (a) exploded view, layout of: (b) the top layer, (c) the second layer, (d) the third layer, (e) the fourth layer and (f) the bottom layer as well as (g) a close up view of the diodes orientations. The geometrical parameters are: $P=15$, $L_1=5.53$, $L_2=1.35$, $L_3=3.2$, $L_4=1.9$, $L_5=0.9$, $L_6=3.2$, $L_7=2$, $L_8=4.86$, $L_9=1.94$, $L_{10}=4.56$, $W_1=5.05$, $W_2=0.21$, $W_3=0.4$, $W_4=0.66$, $W_5=0.66$, $W_6=0.127$, $d_1=0.25$, $d_2=0.45$, $d_3=0.66$, $d_4=1.55$, $d_5=0.55$, $d_6=2$, $d_7=0.85$, $d_8=0.76$, $R_1=3.2$, $R_2=3.6$, $L_{V1}=2.02$, $L_{V2}=0.34$, $L_{V3}=0.45$, $L_{V4}=0.55$, $h_1=0.2$, $h_2=0.2$, $h_3=1.52$, $h_4=0.2$ (unit: mm).

manner. Varactor diodes can also be applied to adjust the reflection phase of each orthogonal linear polarization and hence manipulate the phase of the reflected CP wave [23]. Mechanical tuning method using motor array to control the reflectarray elements presents generally encouraging performances including a wide bandwidth and low sidelobe levels, although the aperture efficiency is not as high as expected due to the lower spillover efficiency [18]. However, the tuning speed and the high profile of the motor-integrated reflector can be the major concerns associated with this approach. While electronically reconfigurable CP reflectarray with continuous phase adjustment has been demonstrated by incorporating varactor diodes [23], the element efficiency and the bandwidth of the work are found to be limited. Method based on PIN diodes is an overall good candidate for designing electrically reconfigurable CP reflectarrays with a moderate cost, small insertion loss and low biasing complexity. Nonetheless, phase resolution of the reported designs is limited to one bit, leading to a relatively low aperture efficiency and high sidelobe levels. Besides, improving the bandwidth of the microstrip-patch based elements is still challenging.

In this paper, a 2-bit fully reconfigurable CP reflectarray using PIN diode switches is proposed, designed and demonstrated. Interlaced and strongly coupled crossed-bowtie patches are exploited to realize the 2-bit phase adjustment and, at the same time, overcome the narrow bandwidth issue. Concerns regarding the practical implementation difficulties are well addressed with a simple biasing circuit design. The CP RRA also highlights a wide beam scanning range and low sidelobes. The paper is organized as follows. Section II introduces the configuration and the design of the proposed 2-bit CP RRA unit cell. Section III describes the

implementation of the RRA prototype and the experimental demonstration of the two-dimensional beam scanning capability. Finally, a conclusion is drawn in Section IV.

II. 2-BIT RECONFIGURABLE CP UNIT-CELL: DESIGN AND ANALYSIS

The electronically tunable element is designed based on the element rotation approach [20], where a CP feed is adopted to illuminate the reflector and the phase of the scattered CP wave is altered by varying the rotational angle of the element. To realize 2-bit phase adjustment, the angular orientation of the element needs to be rotated by as much as 135° with a uniform step of 45° (because the change in CP reflection phase is twice that of the element rotation angle [20]). Since the element in an electronically RRA is physically fixed, the states of the incorporated PIN diode switches are therefore reconfigured to geometrically rotate the element and electronically adjust the CP phase.

A. Unit-cell configuration and analysis

The proposed element consists of four pairs of bowtie patches distributed annularly surrounding the center of the unit-cell, as depicted in Fig. 1. The patches are designed to be in close proximity to each other, i.e., a small axial gap width (W_2) is maintained, for creating a strong mutual parasitic effect and ultimately broadening the element bandwidth. Four pairs of PIN diodes (MADP-000907-14020 from MACOM Technologies) are used to serially connect the two arms of the bowtie patches. Specifically, the eight diodes are divided into two groups, each containing four diodes loaded to bowtie patches lie in orthogonal directions, which are then biased by two DC sources (the DC voltages A and B in Fig. 1(a)),

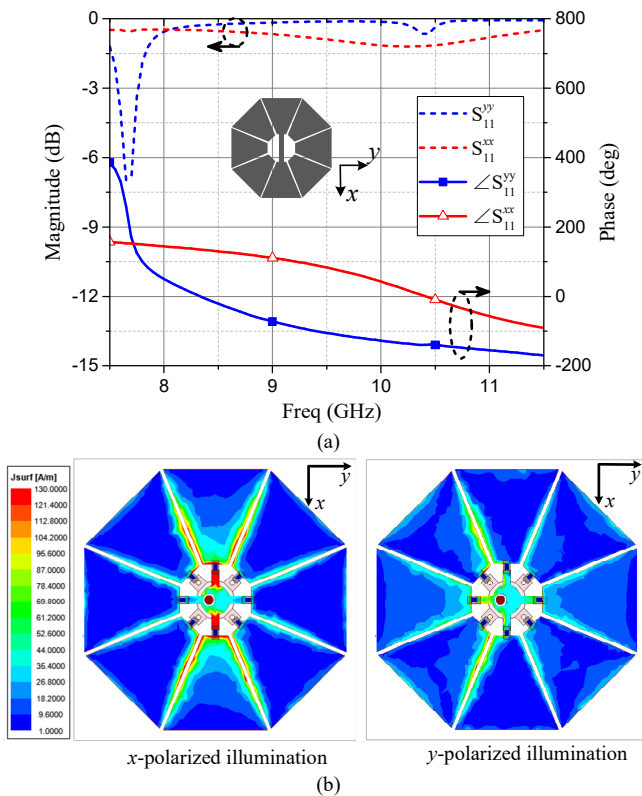


Fig. 2. Simulated reflection coefficients (a) and current distributions (b) of the proposed RRA element under x - and y -polarized plane-wave illuminations, when the two diodes along the x -direction are activated (see the insert for the ideal unit-cell configuration in this case).

respectively. Biasing voltages are provided to the innermost ends of the diodes using the two plated through-holes (PTHs) while the outermost ends of the diodes are all shorted to the ground by blind vias that are introduced on the patches. Noted that the orientations of the diodes are arranged in such a way (see Fig. 1(g)) that the two pairs of diodes in each group always have opposite states, i.e., one pair being forward biased and the other reverse biased and vice versa. The RF filters and DC distributing networks are placed underneath the ground plane so that their interference with the RF signal can be minimized.

(a). Design principle of the CP reflectarray element

As a general design principle, improving the cross-polarization discrimination (XPD) is of paramount interest for achieving a high-performance CP reflectarray unit-cell. Suppressing the cross-polarized CP component, i.e., the component that has a reversed handedness from the incident CP wave and whose phase does not depend on the element rotation, can be realized by introducing a proper degree of anisotropy into the unit-cell that gives rise to a 180° difference in the reflection phase shift between the two orthogonal linear polarizations [20]. Toward this end, a perturbation can be introduced by activating the two diodes associated with a single pair of patches. This opens a new current path to bridge the two halves of the particular bowtie and hence changes the scattering property of the corresponding linear polarization. As an example, the resonance of the element upon x -polarized normal

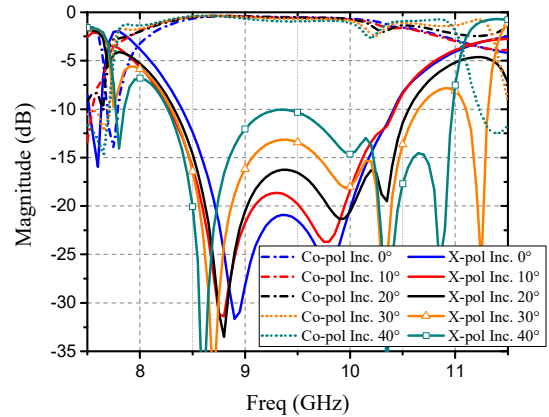


Fig. 3. Simulated reflection coefficients of the co-polarized and cross-polarized CP components for the element under CP wave incidence with different oblique angles.





incidence is noticeably altered when the two diodes in x -direction are forward biased, as compared to that upon the y -polarized illumination (see Fig. 2(a)). The simulated surface current distributions in Fig. 2(b) also validate the different element behavior and resonance under the two orthogonal linear-polarization illuminations. A stable difference of around 180° in phase shift is observed between the x - and y -polarizations in the back-scattered field across a wide frequency range. The magnitudes of the reflection coefficients for co- and cross-polarized CP components are accordingly reported in Fig. 3 (see the solid and dotted blue lines for normal incidence). As it is shown, a unit-cell CP bandwidth of over 20% and an insertion loss mostly within 1.5 dB are achieved.

The sensitivity of element CP performance to the incident angle of the plane-wave excitation is also examined, as sketched in Fig. 3. It is observed that the cross-polarization level can be suppressed to be at least 10 dB lower than the co-polarization over a wide band if the incident angle doesn't exceed 40° , which holds for the most elements across the aperture when a 30-degree offset feeding configuration is adopted (described later). Performances of the edge elements with larger oblique incident angle will be less satisfactory. But their influences on the performance of the whole space-fed array can be limited [24]. Therefore, the proposed crossed-bowtie patch element can be used as a suitable unit-cell for designing wideband CP reflectarrays. The optimized geometrical specifications of the proposed element are listed in the caption of Fig. 1.

(b). Achieving the reconfigurable CP reflection phase

The element reconfigurability can be obtained by applying different sets of DC voltages to the diodes. The orientations of the diodes are given in Fig. 1(g). It can be seen that by providing a positive or negative DC voltage to either of the two biasing lines (denoted in brown and olive in Fig. 1) and connecting the antenna ground plane to the DC zero, four operation states that demonstrate different angular rotation movement of the unit-cell can be achieved. The ideal configuration and required DC voltages for each element state are provided in Table I. The equivalent circuit models of the

TABLE I
REQUIRED BIASING VOLTAGES AND THE IDEAL ELEMENT CONFIGURATIONS OF
DIFFERENT ELEMENT STATES

Element state	DC voltage A	DC voltage B	Ideal element configuration	Reflection phase
#1	0	$-V_f$		0°
#2	$+V_f$	0		90°
#3	0	$+V_f$		180°
#4	$-V_f$	0		270°

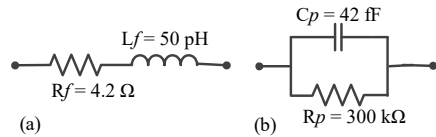


Fig. 4. Equivalent circuit model of the adopted diode in: (a) on and (b) off states.

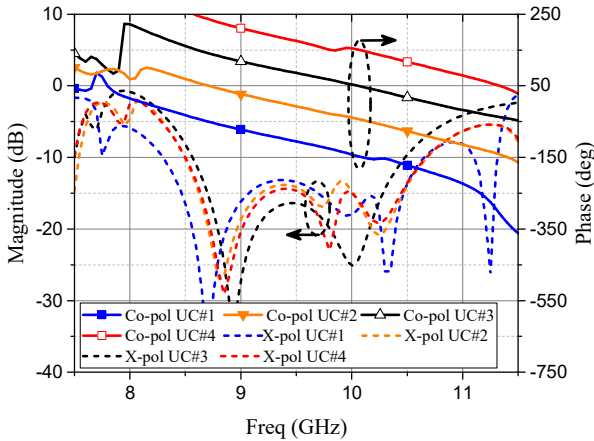


Fig. 5. Phases of the reflection coefficients of the co-polarization component and magnitudes of the reflection coefficients of the cross-polarization component for the four different element states under oblique incidence with an angle of 30° .

PIN diode in both on and off states are extracted from measurement [13] and can be found in Fig. 4.

The co-polarization phases and the cross-polarization magnitudes of the scattered field are plotted in Fig. 5 for the four states of the unit-cell (oblique incident angle of 30° is assumed here). As illustrated, the magnitudes of the reflected crossed-polarized CP components remain lower than -13 dB over a frequency band from 8.5 to 10.3 GHz. Moreover, as desired, four parallel phase responses with a difference of 90° are obtained for the co-polarizations, indicating that a 2-bit phase adjustment can be achieved by switching the element between the four states. It can be inferred that a high cross-polarization suppression and a stable 2-bit phase adjustment are secured over a fractional bandwidth of 20%.

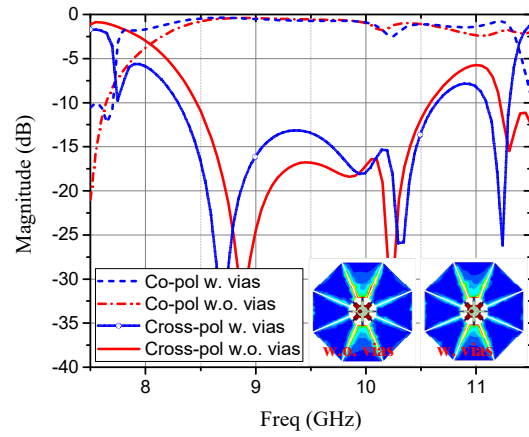


Fig. 6. Simulated reflection coefficients of the co-polarized and cross-polarized CP components for different unit-cell configuration, i.e., with and without the grounding vias.

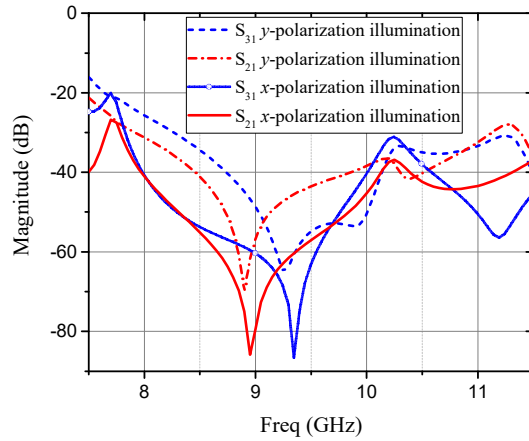


Fig. 7. Simulated coupling coefficients between the incident Floquet port and the ends of the two DC lines that are connected to DC voltages A and B in Fig. 1(a), port 1 represents the incident floquet port, ports 2 and 3 stand for the open ends to DC voltages A and B, respectively.

B. Design of the biasing circuit

A simple and RF-transparent biasing circuit is designed. Only two DC voltages, two DC lines and RF filters are required for each element to switch between the four states.

As depicted in Fig. 1, eight blind vias are utilized to connect a DC zero voltage (in this design, it is supplied to the ground plane) to the outermost ends of the diodes. With optimized via locations, the influence of adding these DC vias, without RF filters, on the element scattering performance could be negligible. As is evidenced from the performance comparison in Fig. 6, the reflection coefficients of the RRA element (in element state #1) upon CP wave incidence remain almost unchanged when the shorting vias are inserted. If one further investigates the surface currents induced on the bowtie patches by an x -polarized plane wave excitation (see the inserts in Fig. 6), it will be identified that the surface currents are weak at the points where the vias are placed. Moreover, grounding of the patches at these locations will not significantly modify the current distribution and hence, the resonance of the element. Therefore, the DC zero can be supplied to one end of all the

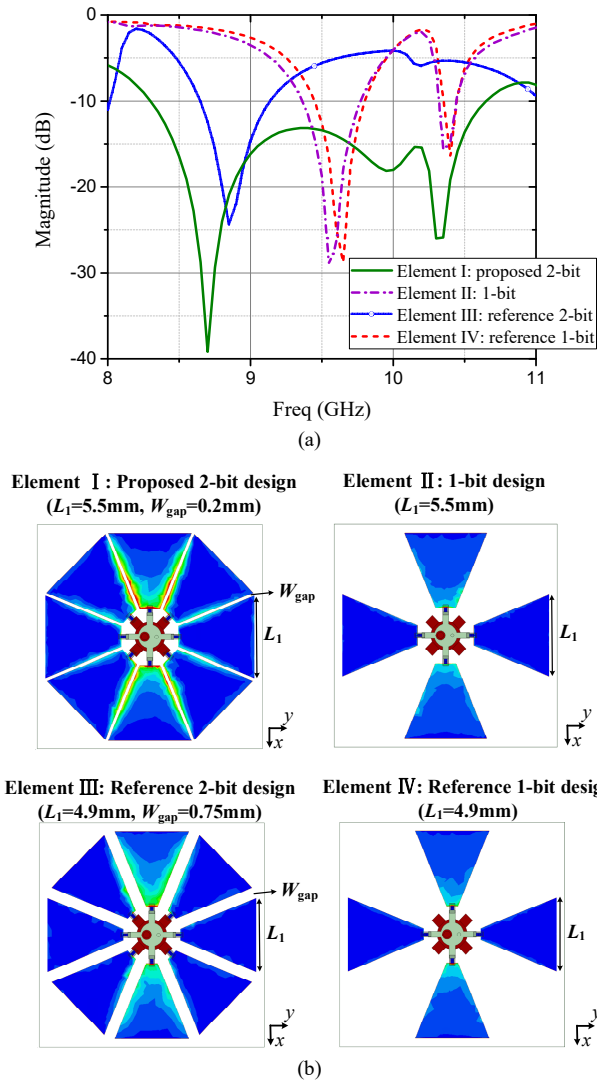


Fig. 8. Simulated reflection coefficients of the cross-polarized CP components (a) and currents distributions under x -polarized illumination when the x -oriented diodes are forward biased (b) for different element configurations, i.e., the 1-bit and 2-bit unit-cells with different patch and gap widths (the results are all obtained under 30° oblique incidence).

eight diodes by merely some RF-transparent blind vias hidden beneath the patches in the antenna layer, which tremendously reduces the overall complexity of the biasing circuit.

In addition, the two DC voltages supplied to the biasing networks beneath the ground plane are distributed to the innermost ends of the diodes through two PTHs. To achieve optimal performance, microstrip low-pass filters are respectively designed along with the two biasing lines. As shown by the simulated coupling coefficients in Fig. 7, the isolation between the incident Floquet port and the two ends of the DC lines can be further improved up to 40 dB after adding the RF filters, demonstrating an overall good shielding of the RF signals. Note that when the filters are not included, coupling between the Floquet port and the DC input points would be around -15 dB.

C. Bandwidth enhancement

From the analysis of the biasing circuit described in the

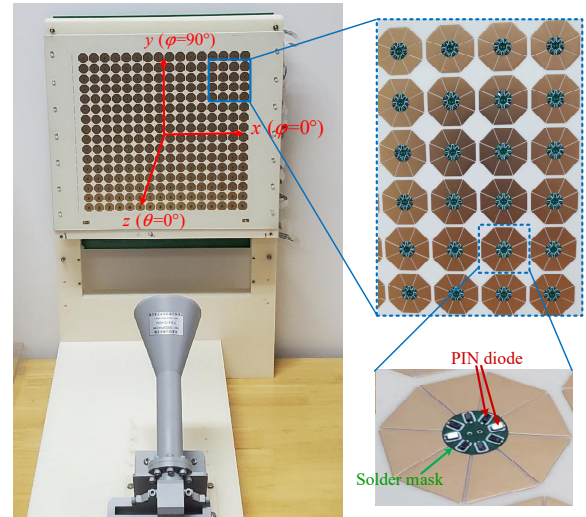


Fig. 9. The fabricated CP RRA prototype: (a) perspective view of the entire antenna, (b) close-up view of the top surface and (c) one particular reconfigurable element.

previous sub-Section, it is clear that the properly designed DC blind vias will not affect the element performance and the RF currents are well confined on the bowtie surfaces. This also suggests that the bowtie patches themselves (not including the grounding vias) are the primary scatters under a plane wave excitation. However, in contrast to multi-resonance unit-cells reported in the broadband CP reflectarray designs [25-30], the crossed-bowtie patch element features single resonance and has a comparatively narrow CP operational bandwidth. This is confirmed by studying the 1-bit unit-cells modified from the proposed 2-bit design, where just one single crossed-bowtie patch is adopted [see the element configurations of Element II and Element IV in Fig. 8(b)]. The simulated reflection coefficients of the 1-bit unit-cells in Fig. 8(a) indicate that the element can hardly provide a large CP bandwidth, regardless of the change in patch width (L_1).

Although duplicating the 1-bit structure and combining two such crossed-bowtie patches together in an interlaced manner improves the phase resolution from one bit to two bits. But that doesn't necessarily contribute to an enhancement in element bandwidth, as demonstrated by the simulated results of the 2-bit unit-cell (Element III) with small patch width and hence wide axial gap [solid blue line in Fig. 8(a)]. In fact, it can be seen the use of the additional crossed-bowtie patch, forming the 2-bit CP element (Element III), only shifts a bit the operating frequency while maintains a similar bandwidth as compared to the corresponding 1-bit design (Element IV) with the same small patch width.

Nonetheless, it is found that the bandwidth of the 2-bit design increases with narrower axial gap. A drastically enhanced operational bandwidth can be achieved by reducing the axial gap width to 0.2 mm (Element I), i.e., less than 0.01 wavelength, as shown by the solid green line in Fig. 8(a). The narrow bandwidth issue can therefore be addressed by using a strongly coupled configuration of the crossed-bowtie patches. To better understand the wideband mechanism, currents distributions of the 1-bit and the 2-bit unit-cells with different

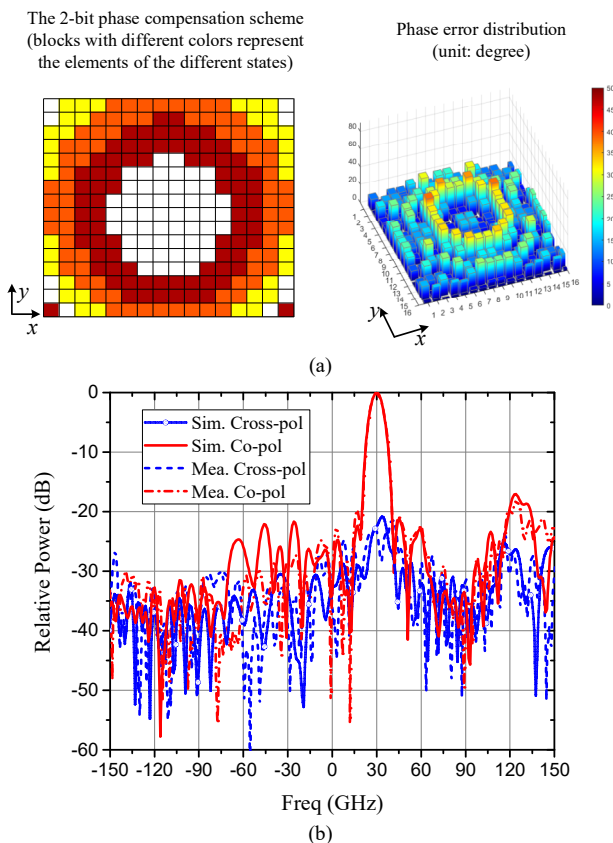


Fig. 10. The optimized phase compensation scheme (a) and measured and simulated radiation patterns (b) of the specular reflection beam in the $\phi=90^\circ$ plane at the center frequency of 9.5 GHz.

patch and gap widths are plotted and compared in Fig. 8(b). Surface currents induced near the patch edges appear to be stronger in the proposed wideband 2-bit design where the gap width is set small. This indicates that a tight coupling can be formed between the neighboring bowtie patches as the gap width decreases. Hence, it is believed the two interlaced and tightly coupled crossed-bowtie patches become parasitic surrounding element for each other and contribute jointly to an enhanced element bandwidth. Sated in another way, aside from increasing the degree of phase agility, the additionally incorporated crossed-bowtie patch also serves to produce a strong parasitic effect that leads to wider element CP bandwidth.

III. REFLECTARRAY IMPLEMENTATION AND MEASUREMENT

A fully reconfigurable CP reflectarray is designed and implemented based on the proposed 2-bit unit-cell to validate the two-dimensional beam scanning capability. The RRA panel is made of 256 reconfigurable unit-cells populated over a 16×16 square aperture (physical size of 240×240 mm²) and is illuminated by a right-hand circularly-polarized (RHCP) horn antenna operating at X-band. Offset feeding configuration with an oblique angle of 30° is considered to alleviate the feed blockage effect. The gain of the feeding horn is about 15 dBic at the center frequency of 9.5 GHz, thus leading to a focal-to-diameter (F/D) ratio of 1.02 to maintain an edge

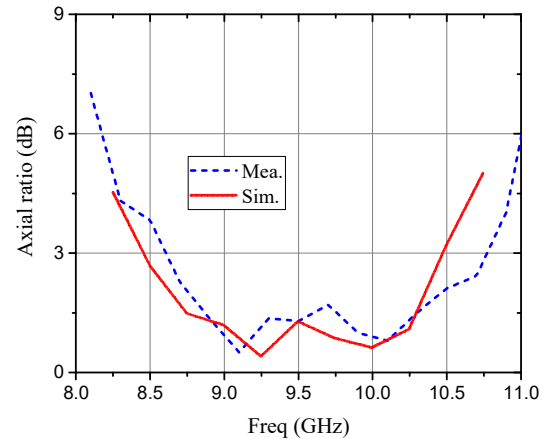


Fig. 11. Measured and simulated axial ratio versus frequency.

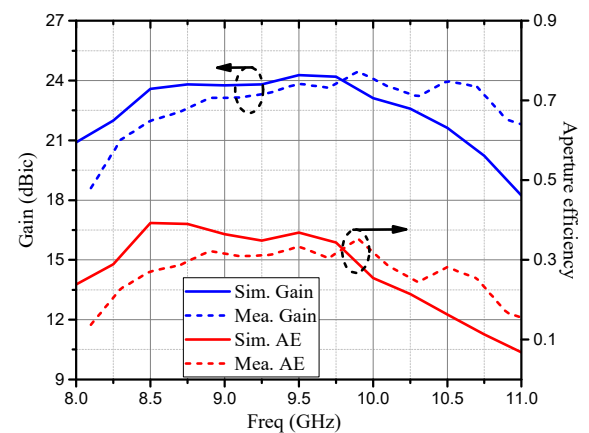


Fig. 12. Measured and simulated gain as well as aperture efficiency versus frequency.

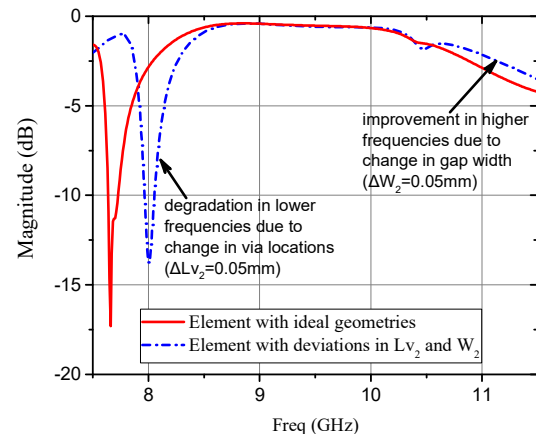


Fig. 13. Simulated element reflection coefficients of the co-polarization component: a sensitivity analysis.

illumination level of -10 dB. Note that circular or elliptical shaped aperture could also be selected if further improvement in aperture efficiency is desired. The phase compensation schemes with 2-bit quantization are optimized by adopting an appropriate reference phase to reduce the phase errors [8, 31]. The performance of the CP RRA is examined using Ansys HFSS with the help of its finite element-boundary integral (FE-BI) boundary condition. To avoid producing dense meshes

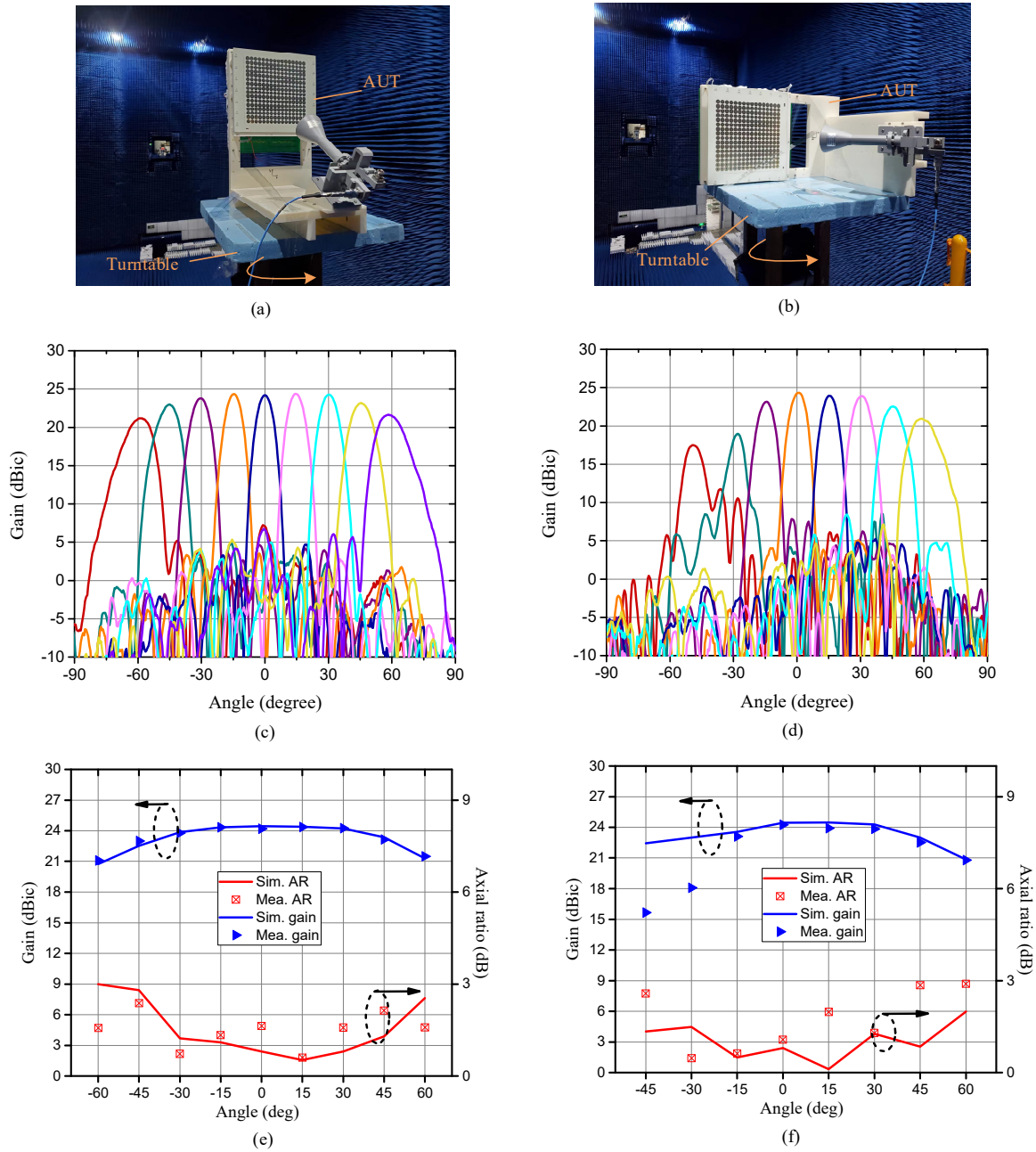


Fig. 14. Photograph of the antenna under test: (a) setup for beam scanning in the $\phi=0^\circ$ plane, (b) setup for beam scanning in the $\phi=90^\circ$; measured results of the scanning patterns: (c) scanning in the $\phi=0^\circ$ plane and (d) scanning in the $\phi=90^\circ$ plane; measured and simulated gain and AR at the main beam directions: (e) scanning in the $\phi=0^\circ$ plane and (f) scanning in the $\phi=90^\circ$ plane. All results are obtained at the center frequency of 9.5 GHz.

at the bottom layer of the reflectarray and reduce the computational time, the long DC lines connected after the RF filters are not included in the simulations. The RRA has been manufactured with standard PCB technologies, which is depicted in Fig. 9.

The fabricated prototype has been characterized under far-field conditions. Radiation patterns of the co- and cross-polarizations, gain and the axial ratio (AR) are measured. To provide an overall evaluation of the bandwidth performance of the beam-scanning RRA, the patterns, gain bandwidth as well as AR bandwidth of the specular reflection beam is first tested and presented. The optimized phase compensation

scheme for generating the specular beam and the corresponding weighted phase errors are plotted in Fig. 10(a). As presented in Fig. 10(b), the expected pencil beam pointing at 30° is well formed. The shape of the main lobe and the locations of the sidelobes are well predicted. The measured XPD is better than 20 dB in the main lobe. Benefiting from the finer phase adjustment of 2-bit resolution, a low sidelobe level of -22 dB is observed, which shows a considerable improvement compared to the 1-bit CP RRA designs [17, 19]. The AR bandwidth of the proposed CP RRA has been also measured as reported in Fig. 11. At most frequencies within the operating frequency range, the measured AR is lower than 1.5 dB. A 3-dB AR bandwidth

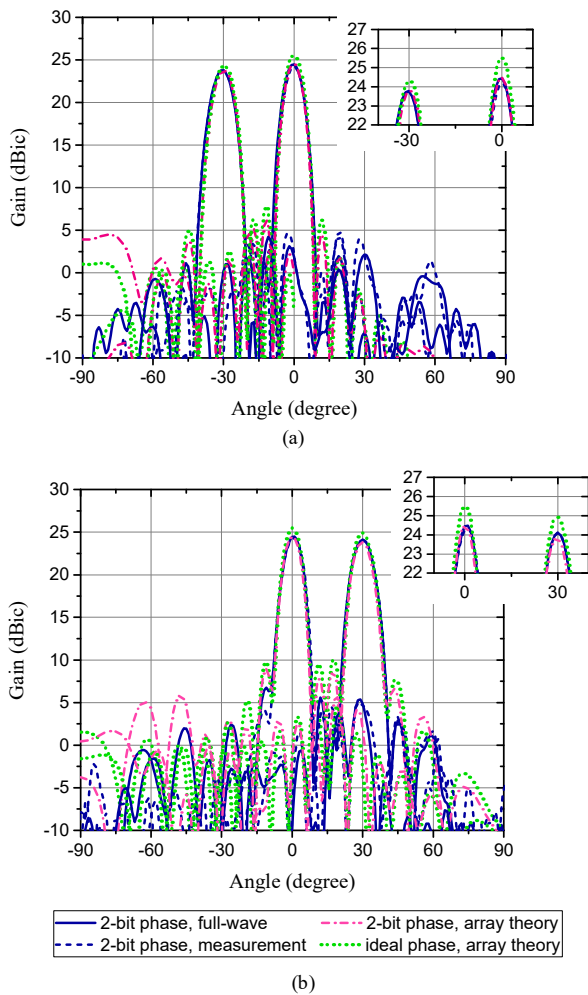


Fig. 15. Radiation patterns obtained from full-wave simulation, measurement and array theory approach: (a) two selected scanning beams in the $\phi=0^\circ$ plane and (b) two selected scanning beams in the $\phi=90^\circ$ plane.

of 22%, covering from 8.6 to 10.7 GHz, is experimentally obtained. Aside from a slight shift in frequency, the measured results agree well with those obtained from full-wave simulation. The simulated and measured gains and the corresponding aperture efficiencies are plotted in Fig. 12. The peak gain reaches 24.5 dBic at the frequency point of 9.9 GHz. A wide 3-dB gain bandwidth of 28% (from 8.6 to 11 GHz) is obtained. The discrepancy between simulation and measurement is suspected to be caused by the fabrication uncertainties (possibly the deviations of several geometrical parameters). We have run a number of parametric studies to examine the most sensitive parameters. As can be deduced from the discrepancy between simulation and measurement, the actual element response at higher frequencies is better than prediction and the insertion loss at lower frequencies becomes larger. Two critical parameters have been identified accordingly, i.e., the gap width between patches (W_2) and the location of the DC vias (L_{V2}). The results considering a possible combined deviation in both W_2 and L_{V2} is depicted in Fig. 13, which shows a similar frequency shifting tendency as observed in the measured results of Fig. 12. An encouraging peak

aperture efficiency of 35% is realized, owing to the improved phase resolution and low insertion loss of the proposed reconfigurable unit-cell. Furthermore, the aperture efficiency of the RRA remains higher than 30% in a comparatively broad frequency range spanning from 8.8 to 10 GHz.

Two-dimensional beam scanning of the proposed CP RRA is also validated. Various beams that point at different elevation angles in two cutting planes, i.e., the xz - and yz -planes, are realized. More precisely, beam scanning in the xz -plane has been demonstrated by steering the main beam from -60° to 60° with a uniform step of 15° . The corresponding measured radiation patterns are shown in Fig. 14(c). In all cases, the beam quality is very satisfactory, with the pencil beams well generated at the pre-defined angles and the measured sidelobe levels around -20 dB below the maximum. The antenna gain stays quite stable when the beam is steered within $\pm 30^\circ$, attaining a gain variation smaller than 1 dB. A wide scanning range up to almost 120° is achieved with scanning loss of about 3.2 dB at $\pm 60^\circ$. Moreover, Fig. 14(e) also shows that the measured antenna gain is in good agreement with the simulated data, and the AR remains below 3 dB over the antenna field of view. High-quality CP is especially obtained within the angular range spanning from -30° to 30° .

A number of beam directions have been also selected to investigate the beam scanning capability in the yz -plane. The radiation patterns measured for the forward reflection beams are all very satisfactory, and the antenna gains agree with those predicted by simulations. However in this cutting plane, the feed blockage becomes severe, especially for those beams pointed at the backward reflection region. As indicated by the experimental results in Figs. 13(d) and 13(f), quality of the beams pointing at the backward region where the feeding horn is situated can be affected: when the beam scans to, or beyond, -30° , the radiation pattern becomes noticeably distorted. Besides, the antenna gain drops and becomes lower than the simulated values. This is caused by the large flange and bulky orthomode transducer adopted at the end of this commercial CP horn, which are not included in the full-wave simulation. The scan loss remains below 3 dB when the beam scans within the angular range from -15° to 60° . Moreover, AR value of lower than 3dB has been obtained for all the scanning beams in this cutting plane. Consequently, the two-dimensional beam scanning capability of the CP RRA is properly verified.

To investigate the effect of quantized phase on the scanning performance, the scanning beam patterns of the reflectarray have also been calculated based on the array theory approach. Two-bit and ideal phase compensations are respectively considered. Scanning performances in both planes (by taking a scan angle of 30° as an example) have been examined. The scanning patterns obtained from full-wave simulation, measurement and the array theory approach are compared and plotted in Fig. 15. It can be inferred from the plotted scanning results that the scanning loss is mainly caused by scanning itself, and the 2-bit phase quantization does not introduce extra scanning loss. By comparing the results obtained from the array theory approach, it is found that the 2-bit phase quantization would mainly lead to a decrease in antenna gain. Generally, a

TABLE II
PERFORMANCE COMPARISON WITH THE REPORTED CP RECONFIGURABLE REFLECTARRAYS

Ref. no.	Tuning method	Phase bit	Element BW	Array BW	Gain (dBic)	Aperture Eff.	SLL (dB)	Scan loss @60° (dB)
[18]	Motor	>3	35%	30%	29.2	35%	-25	4
[17]	PIN diode	1	20%	n.a.	17.5	15%	-11	n.a.
[19]	PIN diode	1	7.4%	5.6%	21.8	20%	-13	4.5
[23]	Varactor diode	>3	n.a.	7.6%	14	13.3%	-10	n.a.
Proposed	PIN diode	2	21%	22%	24.5	35%	-20	3.2

Note: [n.a.] = not available, [Array BW] = the common 3-dB gain and 3-dB AR bandwidth of the reflectarray.

gain loss of around 1 dB will be induced as compared to the ideal phase compensation case (this agrees with the results reported in [32], where the authors show that 2-bit phase quantization would cause 0.9 dB gain loss for a similar-size reflectarray). The impact on sidelobe and beamwidth by the 2-bit quantization is not significant.

The performance of the proposed 2-bit CP RRA is summarized in Table II and compared with the state-of-the-art CP RRA designs. The proposed design shows the advantage of wide element and array bandwidths of over 20% as compared to the designs based on PIN diodes and varactor diodes. A high aperture efficiency of 35% has been achieved, which outperforms not only the reported electronically RRA but also the mechanical-tuning design with a phase adjustment of finer than 3 bits. The low sidelobe level of -20 dB and large scanning range covering almost $\pm 60^\circ$ are both attractive features that distinguish the proposed design with others.

When comparing to a similar phased array, the proposed design also shows advantages in cost and efficiency. The major differences between a phased array and the reconfigurable reflectarray lie in their feeding and the phase adjustment mechanisms. These differences will mainly affect the aperture efficiency and the element phase error. For designing the phased array, most commercially available phase shifters can provide 3-bit phase adjustment, which means a gain improvement of around 0.7 dB comparing to the 2-bit quantization adopted in the proposed antenna. But losses from the feeding network (~ 2 dB) and the insertion loss of the phase shifter (~ 3 dB) are relatively high. On the other hand, the proposed reconfigurable reflectarray is spatially fed and uses diodes to manipulate the element phase. The spillover efficiency and tapered illumination efficiency are around -1.1 dB and -0.7 dB, respectively. Element insertion loss is roughly 1.5 dB as can be seen from the unit-cell simulation. Total loss is around 4 dB for the proposed reflectarray.

Finally, a few technical concerns regarding the switching time of the array, the possibility of extending the proposed design to higher frequency and increasing the element phase resolution, are clarified here. Concerning the switching time, because currently a switch array is adopted to manually supply each element with the desired DC voltage and configure the element state, we are unfortunately not able to provide a measured data. But the response time of a reconfigurable reflectarray using the same PIN diode has been reported in [8], which provides some valuable information regarding this point. It has been revealed the time for the diodes themselves to

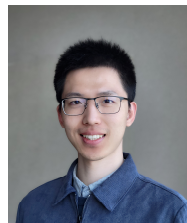
change the state is negligible (only several nanoseconds), and the primary factors that determine the total response time are the clock rate of the FPGA and the wiring mechanism for controlling the array. When considering moving towards higher frequency, the fabrication tolerance of the standard PCB technology will be a stranglehold. As clarified, the element performance can be sensitive to several parameters when the gap width is small (i.e., for achieving enhanced element bandwidth). To ensure the desired wideband performance and minimize the possible frequency shift caused by manufacturing uncertainties, the design is carried out at X band. But if bandwidth enhancement is not the primary concern (i.e., one can accept a bit sacrificed bandwidth and allow the use of wider gaps), it is believed that this design can be extended to Ka band with acceptable performance (as the narrower-bandwidth element would be much less sensitive to the fabrication uncertainties and the PIN diode has been validated for operating up to 30 GHz [13]). As for the potential increase in the number of phase states, it is a trade-off between complexity and performance. The 2-bit phase quantization has been selected in our design. The first reason for this selection is that, as far as the array performance is concerned (including aperture efficiency, sidelobe levels), 2-bit design provides reasonably good results that are close to those of a 3-bit design, as has also been depicted in [32]. The other reason is that increasing the element phase states (e.g., from 2-bit to 3-bit quantization) means not only doubled number of PIN diodes, independent DC voltages, more PCB layers but also placing stricter geometrical constraints on the element, which leads to less degree of design freedom and possibly narrower bandwidth.

IV. CONCLUSION

A wideband, wide-scanning-angle and high-efficiency 2-bit CP RRA has been presented using unit-cells based on the interlaced and strongly-coupled crossed-bowtie patches. Aside from squeezing two interlaced structures into one unit-cell to increase the phase resolution, the proposed broadband technique, simple biasing circuitry and low-loss reconfigurable mechanism designs are important contributions of this work. The antenna prototype has demonstrated a 3-dB bandwidth of 22% (in terms of both antenna gain and AR), a peak gain of 24.5 dBic and an aperture efficiency of 35%. Wide beam scanning range covering from -60° to 60° has been also archived with the scan loss of up to around 3 dB.

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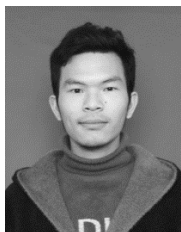


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