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# Polarization Reconfigurable Aperture-Fed Patch Antenna and Array

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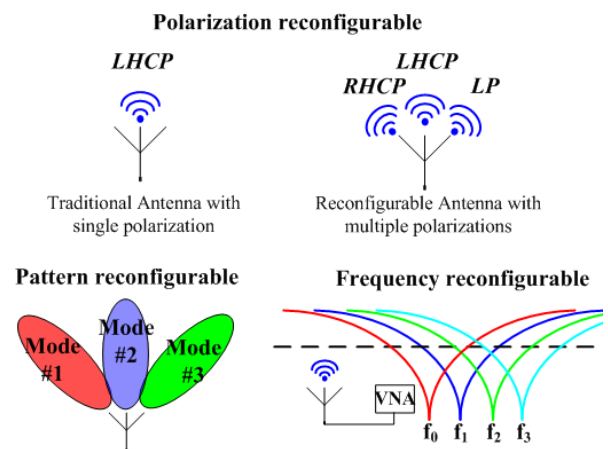
**ABSTRACT** This paper presents a reconfigurable aperture-fed patch antenna array for  $\pm 45^\circ$  polarizations. First, a new method to realize the reconfigurable  $\pm 45^\circ$  polarizations is proposed. It introduces controllable RF switches on a cross-aperture to excite a square patch for two orthogonal polarizations. The RF switches are controlled by two sets of DC biases, which could select the polarization through the reconfigurable aperture. Second, two patch antennas based on cross-aperture excitation are discussed. The first structure uses a split ground plane with four switches, while the other one employs a united ground plane with eight switches. Both antennas operate well as the single element. However, only the antenna with a united ground is suitable for developing a reconfigurable dual-polarized antenna array, owing to its simple DC biasing lines and the reconfigurable-controlling network. Both simulation and experiment studies were examined to verify the proposed design. The measured 10-dB impedance bandwidth of the array is 9.3%, which can cover the 2.4-GHz WLAN band. The desired radiation patterns were observed with a maximum gain of 13.5 dBi. The proposed antenna array has low cross-polarization and stable gain across the entire operating bandwidth.

**INDEX TERMS** Polarization reconfigurable antenna array, aperture-fed patch antenna,  $\pm 45^\circ$  Polarization, PIN diodes.

## I. INTRODUCTION

Reconfigurable antennas have drawn much attention in modern wireless communication systems due to the merits of enhancing the system capacity, avoiding the multipath effects in wireless channels and enabling polarization coding for digital systems [1]–[3]. In general, three types of reconfigurable antennas are widely studied as seen in Fig. 1. Frequency reconfigurable antennas can sweep the operating frequency as in [4]–[6]. Pattern reconfigurable antennas are able to generate different radiation patterns as in [7]–[9]. In addition, polarization reconfigurable antennas are capable of radiating waves with switchable linear or circular polarizations.

Many efforts have been demonstrated in polarization reconfigurable antennas as in [10]–[17]. Two techniques are mainly adopted to generate switchable polarizations: realizing reconfigurable radiators as in [10]–[14] or designing reconfigurable feeding networks to excite the radiator in order to generate different polarizations as in [15]–[17]. For example, the reported work in [10] introduces PIN diodes on the slots etched on a radiating rectangular patch to construct a reconfigurable patch radiator. By controlling ON/OFF states of these diodes, the broadside radiation patterns with



**FIGURE 1.** Three types of reconfigurable antennas: Polarization, Pattern and Frequency.

orthogonal linear polarizations are switchable. The measured impedance bandwidth is 4.3% and the peak gain is 2.55 dBi. Another design in [11] realizes a reconfigurable circular patch radiator for linear polarization diversity. The broadside peak gain is 7.7 dBi which is higher than that in [10], but the bandwidth is only 0.3%. Moreover, square-patch

radiators in [12]–[14] can also generate the switchable polarizations. The highest broadside gain is 8.45 dBi with the impedance bandwidth of 3.6%. Besides of the reconfigurable radiators, antennas with the reconfigurable networks are also able to achieve polarization diversity. As in [15], a square patch is excited by a reconfigurable network to generate the orthogonal linear polarizations with the bandwidth of 6% and the peak gain of 5.58 dBi. Furthermore, other designs shown in [16]–[17] have the reconfigurable networks to generate either slot mode or monopole mode for polarization diversity with the peak gain of 3 dBi. Above mentioned works [10]–[17] are reconfigurable single antenna elements with low gain.

To improve the gain for reconfigurable antennas, array configurations have been proposed in [18]–[21]. For example, a  $2 \times 2$  square patch array with reconfigurable radiators is described in [18] but no measured results with active RF switches are given. In addition, a  $\pm 45^\circ$  polarization switchable slot-ring array antenna in [19] has the simulated peak gain of 10.9 dBi; nonetheless, only simulated results are given without real implementation. Another work [20] presents a circularly-polarized reconfigurable antenna array designed by LTCC technology. The simulated maximum directivity is 13 dBic but no measured result is provided. A tunable RF MEMS switch for the reconfigurable antenna array [21] demonstrates a design concept without realization. To conclude, no real implementation with RF switches can be found in all the mentioned polarization reconfigurable arrays [18]–[21], only simulated results are presented.

In this paper, we realize the implementation of a  $\pm 45^\circ$  polarization reconfigurable aperture-fed patch antenna array for the first time. A new technique to realize the  $\pm 45^\circ$  polarization reconfigurability is presented, which introduces PIN diodes on a cross aperture feeding structure to excite a square patch. Thanks to its simple DC biasing topology, the single radiating element with the united ground can be easily expanded to an array configuration. To verify the design concept, an implementation of a  $1 \times 4$  aperture-fed patch antenna array is fabricated and examined. Measured results show that the  $\pm 45^\circ$  linear polarizations are switchable by controlling two DC voltages. The overlapped impedance bandwidth for both polarizations is 9.3% which can cover the 2.4 GHz WLAN band. Desired radiation patterns are observed with the maximum gain of 13.5 dBi and the cross polarization ratio level is larger than 10 dB. This polarization reconfigurable antenna with high directivity can be used as base station antennas for WLAN or wireless sensor network systems.

## II. SINGLE ELEMENT DESIGN OF THE $\pm 45^\circ$ POLARIZATION RECONFIGURABLE APERTURE-FED PATCH ANTENNA

### A. OPERATING PRINCIPLE

A new method to achieve the polarization reconfigurability is realized by modifying an aperture-fed patch antenna as shown

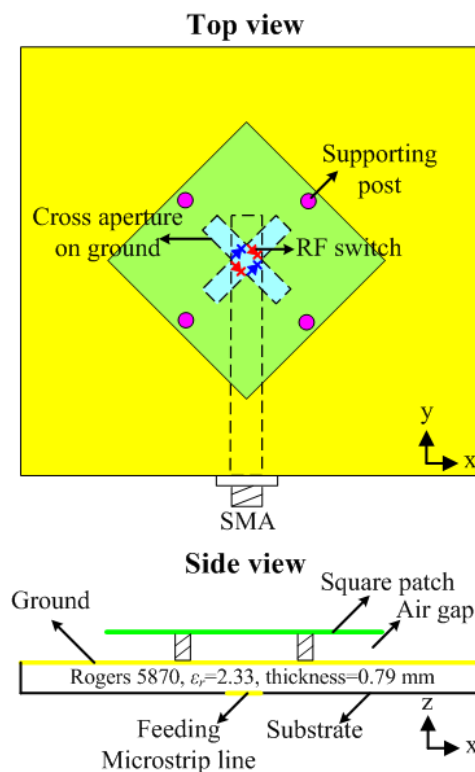


FIGURE 2. Antenna configuration: single element.

in Fig. 2. The aperture-fed patch antenna was fully investigated by D. M. Pozar as in [22]–[23]. It consists of a radiating patch and an aperture feeding structure. A rectangular aperture is commonly etched on the ground and located underneath the center of the patch to couple the electromagnetic fields from the feeding microstrip line. The orientation of the rectangular aperture determines the direction of antenna polarization. Based on this characteristic, we came up with an idea by introducing RF switches connected between a cross aperture to achieve a reconfigurable feeding structure. A square patch is selected as the radiator fed by the cross aperture to form a symmetric configuration. As the result, the  $+45^\circ$  linearly-polarized radiation is generated when the two red switches are turned on and the two blue switches are tuned off as seen in the current distributions of the radiating patch shown in Fig. 3. On the opposite, the  $-45^\circ$  linear polarization will be realized when the two blue switches are turned on and the two red ones are turned off.

### B. IMPLEMENTATION WITH PIN DIODES AND DC BIASING LINES

To realize the design concept, we utilize PIN diodes (Bar50-02L from Infineon Technologies [24]) as switches to reconfigure the structure of cross aperture. As seen in Fig. 4, the diode acts as a short-circuited conductor when it is forward biased. In this state, the equivalent circuit of the diode in RF band is a small parasitic inductance  $L$  in series with a small forward resistance  $R_1$ . On the other hand, the diode

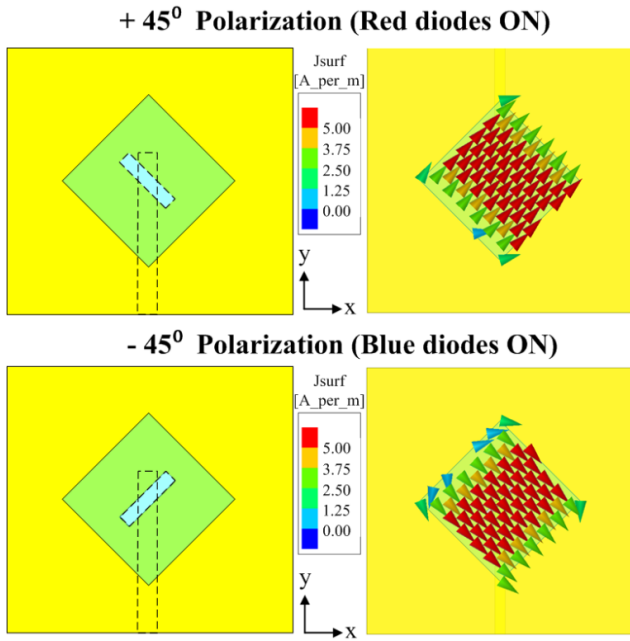


FIGURE 3. Current distributions of the radiating patch in the two states of the  $\pm 45^\circ$  linear polarizations.

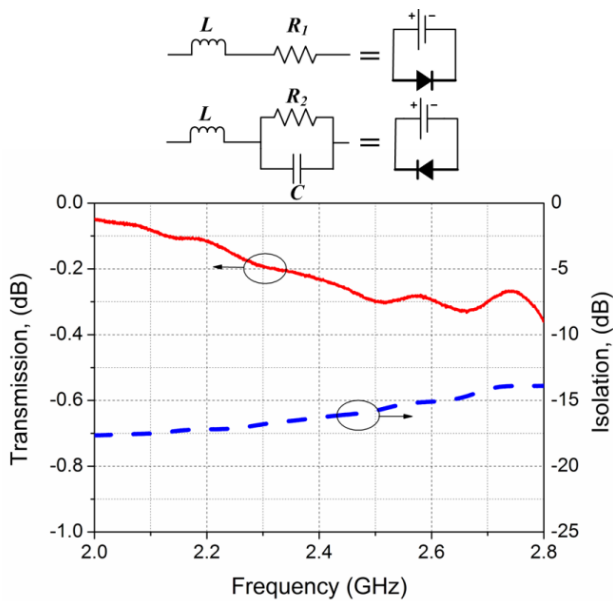


FIGURE 4. Measured characteristics of Infineon Bar50-02L PIN diode.

will act as an open-circuit if it is reversely biased. In this state, the equivalent circuit has the same parasitic inductance  $L$  in series with a large reverse resistance  $R_2$  and a small reverse capacitance  $C$  in parallel. Bar50-02L PIN diode is a suitable candidate to be a RF switch operating at the frequency range from 0 to 6 GHz. Due to the low parasitic inductance  $L$  (0.4 nH), the small forward resistance  $R_1$  (2 ohm), the large reverse resistance  $R_2$  (5K ohm) and the small reverse capacitance  $C$  (0.08 pF), the selected diode shows small insertion loss (less than 0.4 dB) and good isolation (larger than 14 dB)

in our interested band from 2 to 3 GHz. To apply biasing voltages for the diodes, two antenna configurations can be adopted as presented in the following sections.

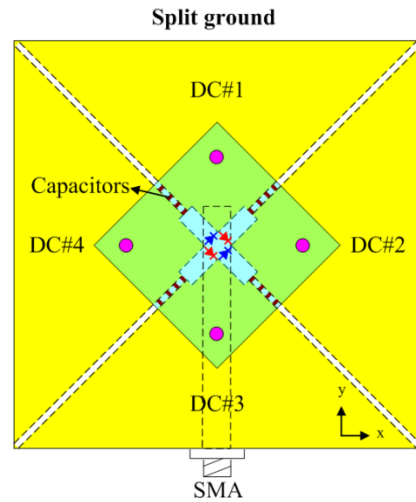


FIGURE 5. Antenna configuration A: four diodes with a split ground.

TABLE 1. Polarizations by different biasing voltages.

DC#1	DC#2	DC#3	DC#4	Polarization
1.5 V	0 V	0 V	1.5 V	+ 45°
0V	0 V	1.5 V	1.5 V	- 45°

1) ANTENNA CONFIGURATION A - FOUR DIODES ON THE CROSS APERTURE WITH A SPLIT GROUND

In order to provide the voltage potential for the four diodes, we divide the ground into four parts as seen in Fig. 5 such that each part is electrically isolated. In this way, we can apply four DC voltages as DC#1, DC#2, DC#3 and DC#4 to control these diodes for reconfiguring antenna polarizations. As shown in Table 1, if DC#1 to DC#4 are biased with the

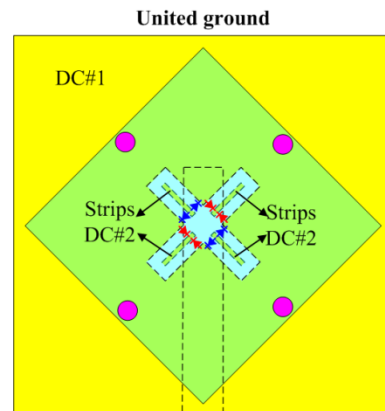


FIGURE 6. Antenna configuration B: eight diodes with the united ground.



voltage 1.5 V, 0 V, 0 V and 1.5 V respectively, the two red diodes are turned on to generate the  $+45^\circ$  polarization. On the other hand, if DC#1 to DC#4 are biased with the voltage 0 V, 0 V, 1.5 V and 1.5 V respectively, the  $-45^\circ$  polarization will be realized. In this configuration, one important consideration is that many capacitors as DC blocks must be placed in the cutting slits between the separated ground planes to maintain the desired operating mode for the patch. The realized design prototype and measured results can be found in [25]. For the single antenna element design, this configuration is acceptable. However, for antenna array design, it is not practical since many cutting slits will be appeared between array elements resulting in complicated DC lines involved. Figure 7 shows the hypothetical implementation of the antenna array with the split ground plane. It cannot be realized since most part of the feeding network will overlap with the cutting slits.

TABLE 2. Polarizations by different biasing voltages.

DC#1	DC#2	Polarization
1.5V	0 V	$+45^\circ$
0 V	1.5 V	$-45^\circ$

2) ANTENNA CONFIGURATION B - EIGHT DIODES ON THE CROSS APERTURE WITH THE UNITED GROUND

In order to extend the design to an array configuration, we figured out another DC biasing structure with the united ground plane as shown in Fig. 6. Four additional copper strips are used and placed at the cross aperture, then two DC biases as DC#1 and DC#2 can realize the polarization reconfigurability when eight diodes are placed as the manner of Fig. 6 illustrated. Table 2 shows the reconfigurable polarizations can be generated by altering the two DC biases. Since this

configuration has the united ground and less DC biases, it is promising to be extended as an antenna array.

III. DESIGN OF THE 1 x 4 POLARIZATION RECONFIGURABLE PATCH ARRAY

A. ANTENNA CONFIGURATION

With the use of the united ground plane configuration, the single antenna element can be easily extended and developed to construct a  $1 \times 4$  aperture-fed patch array as shown in Fig. 8. The antenna array consists of three parts. Firstly, four radiating square patches are on the top with the length of  $L_g$  and the element spacing of  $S_p$ . In this prototype, the patches are made of copper plates and supported by some plastic posts with the diameter of  $D_p$ . Secondly, an aperture-feeding structure is designed on the substrate Rogers 5870, which has the relative permittivity of 2.33 and thickness of 0.79 mm. The ground plane ( $L_g \times W_g$ ) with four cross apertures ( $L_a \times W_a$ ) is on the top layer of the substrate and the microstrip lines of the 1-to-4 power divider are etched on the bottom layer of the substrate. PIN diodes are connected between the ground and the inner strips of the apertures. In addition, all the inner strips are connected together and merge into a single DC line, which is supplied by the voltage DC#2. At the same time, DC#1 is supplied to the ground. In this manner, the DC biasing scheme is the same with the single element design as in Table 2. The  $-45^\circ$  apertures are formed for realizing  $+45^\circ$  polarization if DC#1 and DC#2 are biased with 1.5 V and 0 V respectively. And the  $+45^\circ$  apertures are reconfigured when DC#1 and DC#2 are alternated. In this configuration, only two DC lines are necessary to provide the bias voltages for these diodes. Detailed key antenna parameters are listed in Table 3.

B. DESIGN GUIDELINES FOR THE ANTENNA ARRAY

This section shows the design guidelines for the proposed aperture-fed patch antenna array, including the key parameters of the patch, the apertures, and the feeding network.

Array implementation with a split ground

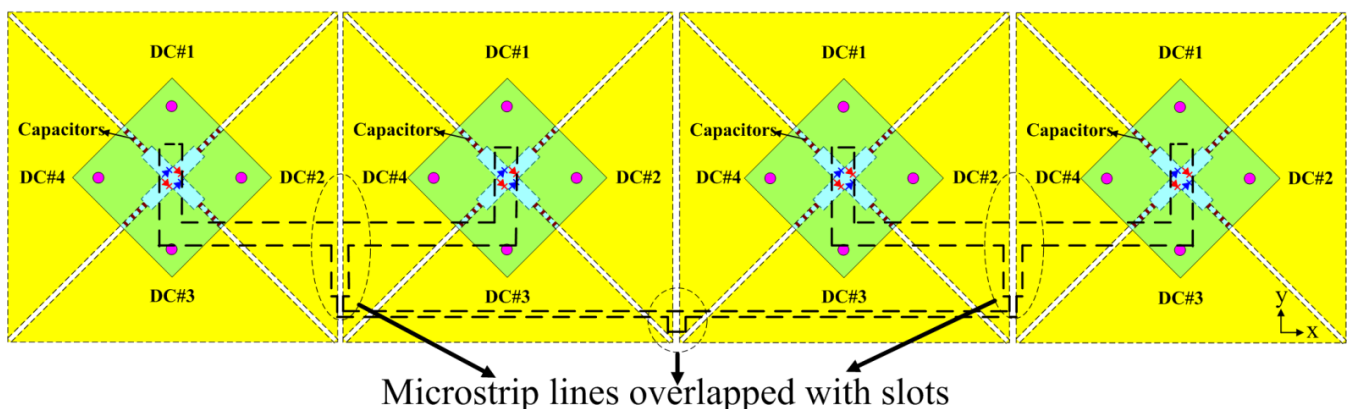


FIGURE 7.  $\pm 45^\circ$  polarizations reconfigurable  $1 \times 4$  antenna array implementation with a split ground.

Array implementation with the united ground  
Top view

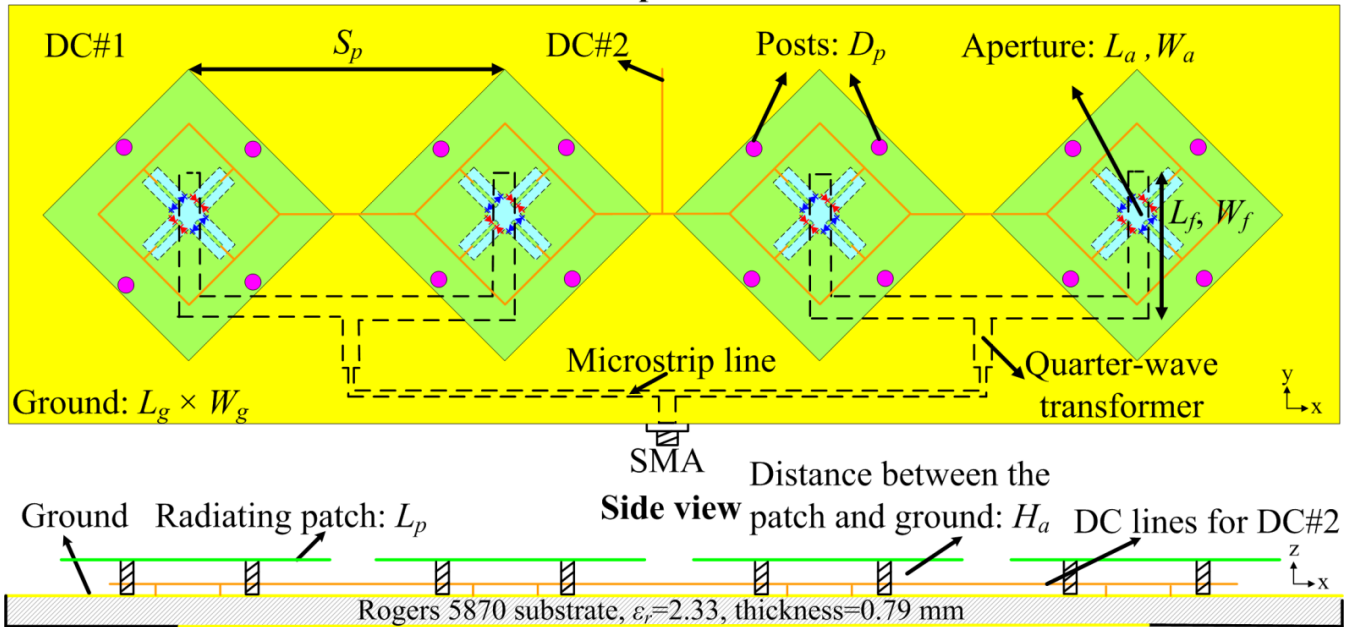


FIGURE 8. ±45° polarizations reconfigurable 1 × 4 antenna array implementation with the united ground.

TABLE 3. Key antenna parameters.

Parameter	Description	Value
$L_p$	Side length of the square patch	52 mm
$H_a$	Height of the patch from the ground plane	4 mm
$S_p$	Spacing between the patches	100 mm
$L_d$	Length of the feeding aperture	19 mm
$W_d$	Width of the feeding aperture	2 mm
$L_f$	Length of the feeding line under patch	45.5 mm
$W_f$	Width of the feeding line under patch a	4.6 mm
$L_g$	Length of the ground	420 mm
$W_g$	Width of the ground	160 mm
$D_p$	Diameter of the supporting posts	3 mm
$H_r$	Distance between antenna and reflector	20 mm

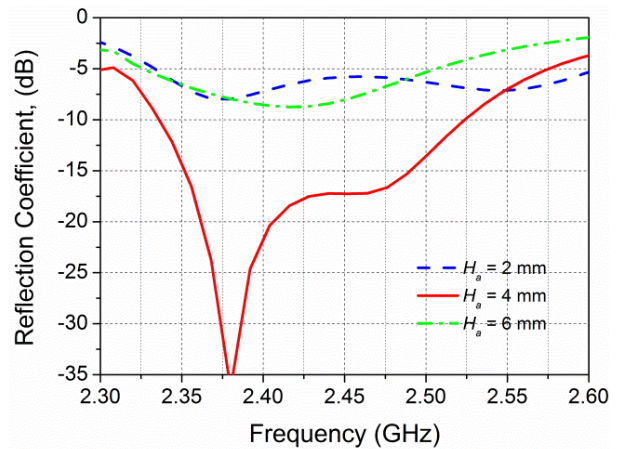


FIGURE 9. Simulated reflection coefficients for different air gap  $H_a$ .

1) RADIATING PATCHES

The length of the patch determines the resonant frequency and can be set to half wavelength  $\lambda_g/2$  at the center frequency. The patches can be either supported by a dielectric substrate or suspended in the air with fixing by some plastic posts. In order to widen the bandwidth and eliminate the surface wave, we choose the latter case. Since the proposed antenna element is excited by aperture-coupled technique, the height  $H_a$  of the patches from the ground plane determines the coupling level from the apertures, thus it is sensitive to the impedance matching. Figure 9 shows the reflection coefficients of the proposed antenna array for different  $H_a$ . Finally,  $H_a = 4$  mm is chosen due to its best impedance

matching among all cases. In antenna array design, one important concern is the element spacing which determines the radiation pattern. Figure 10 shows the radiation patterns of the proposed antenna array with different element spacing  $S_p$  from 80 mm to 120 mm. The broadside directivity becomes higher when the spacing is increased, but the side lobes go up and whole antenna size becomes larger. To balance, we set the element spacing  $S_p = 100$  mm ( $0.8\lambda_g$ ).

2) FEEDING APERTURES

Feeding aperture is another key parameter which affects the coupling level. The aperture is primarily determined by the

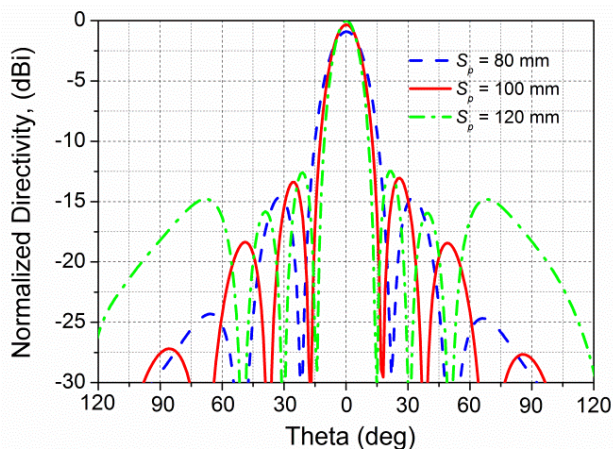


FIGURE 10. Simulated radiation patterns of the antenna array at the horizontal plane ( $\varphi = 0^\circ$ ) and 2.45GHz with different element spacing  $S_p$ .

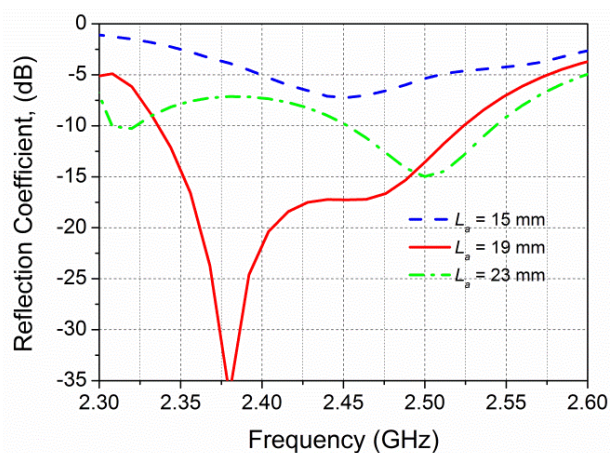


FIGURE 11. Simulated reflection coefficients for different aperture length  $L_a$  when the width  $W_a$  is fixed to 2 mm.

length of the aperture  $L_a$ . Typically, the ratio of aperture width to length is about 1/10. Figure 11 shows the reflection coefficients for different  $L_a$ . We can see  $L_a$  is sensitive to the impedance matching. We chose  $L_a = 19$  mm for the final design owing to the best impedance bandwidth obtained.

### 3) FEEDING NETWORK

Feeding network is indispensable for an antenna array. In this design, we use a conventional 1-to-4 power divider to distribute even power to four antenna elements.

The width  $W_f$  and length  $L_f$  of the power divider affect the coupling to the patches. Finally,  $W_f = 4.6$  mm and  $L_f = 45.5$  mm are used in the proposed design after optimization.

### C. EFFECT OF ANTENNA ABOVE A REFLECTOR

Since the proposed array has cross apertures and the microstrip line network for exciting antenna elements, it is suggested placing a metallic reflector below the array to avoid any interference from any environmental causes as well as

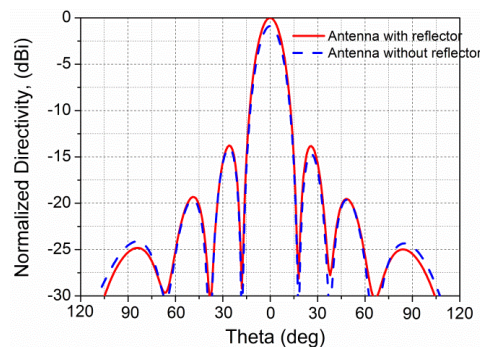


FIGURE 12. Simulated radiation patterns of the antenna array at the horizontal plane ( $\varphi = 0^\circ$ ) and 2.45GHz with and without the reflector.

to suppress the back lobe radiation. In addition, the presence of the reflector will enhance the broadside directivity of the radiation pattern. Figure 12 shows the radiation patterns of the antenna with and without the reflector. The reflector has the same size as the ground of the antenna and is placed at the distance  $H_r$  of 20 mm below the array. The impedance matching is insensitive to the presence of the reflector but the broadside directivity increases by 0.9 dBi. Therefore, in our final implementation, the reflector is used.

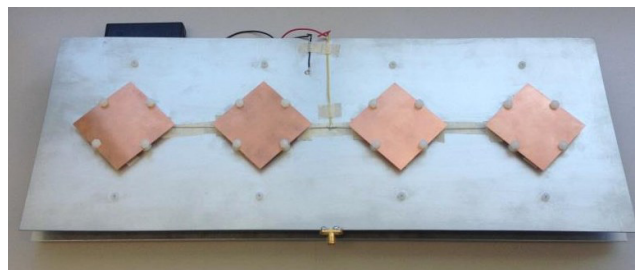


FIGURE 13. Prototype of the fabricated antenna.

## IV. MEASURED RESULTS

To validate the design concept, the implementation of the polarization reconfigurable aperture-fed patch antenna array is realized as shown in Fig. 13. From the fabricated prototype, we can see that the antenna is fixed above a metallic reflector. All the diodes are located at cross apertures. All DC lines are placed around the cross apertures and are put very close to the ground to avoid the interference of antenna radiation. The 1.5 V batteries are used as the DC supply source. All the simulated results were obtained from Ansoft HFSS software. The reflection coefficients were measured by Agilent Vector Network Analyzer and the antenna radiation patterns were measured in SATIMO near-field measurement system.

For the fabricated antenna, the  $\pm 45^\circ$  polarizations are switchable by simply altering the two DC supply voltages. Figure 14 shows the measured reflection coefficients for both  $\pm 45^\circ$  modes. The overlapped impedance bandwidth is 9.3% from 2.25 to 2.47 GHz. The measured bandwidth has shifted 0.08 GHz lower than the simulated one as in Fig. 9 due



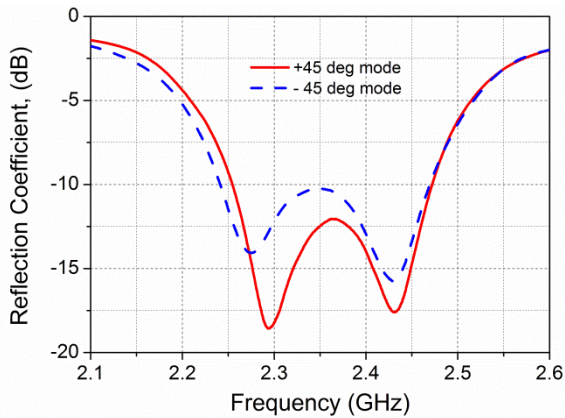


FIGURE 14. Measured reflection coefficients for both modes.

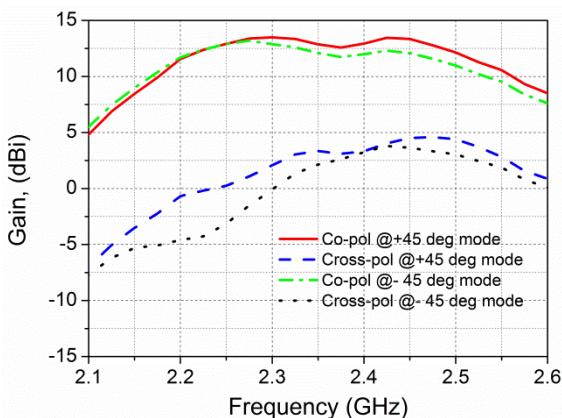


FIGURE 15. Measured gain versus frequency at the broadside direction for both modes.

to the fabrication tolerance and the unpredictable effect of the diodes. The relative bandwidths of both simulated and measured results are similar. In later design process, we can shift the bandwidth back to our target by adjusting the antenna structure through the design guidelines discussed in Section B of Part III.

Figure 15 shows the measured gain versus frequency at the broadside direction for both modes. The result exhibits that the gain is stable across the operating bandwidth with the maximum co-pol gain of 13.5 dBi and the cross polarization ratio is more than 10 dB.

Figures 16 (a) and (b) show that the measured and simulated radiation patterns are in good agreement at both the horizontal and vertical planes for the two modes. Narrow beams are observed in the horizontal plane and broad beams are found in the vertical plane as the typical linear antenna array. The first side lobe is less than  $-12.5$  dBi and the front to back ratio is more than 25 dB. The 3-dB beamwidth in the vertical plane is 53 degree for  $+45^\circ$  polarization mode and 50 degree for  $-45^\circ$  polarization mode.

To sum up, all above measured results show that our proposed antenna array can realize the reconfigurable  $\pm 45^\circ$  polarizations with stable gain and good

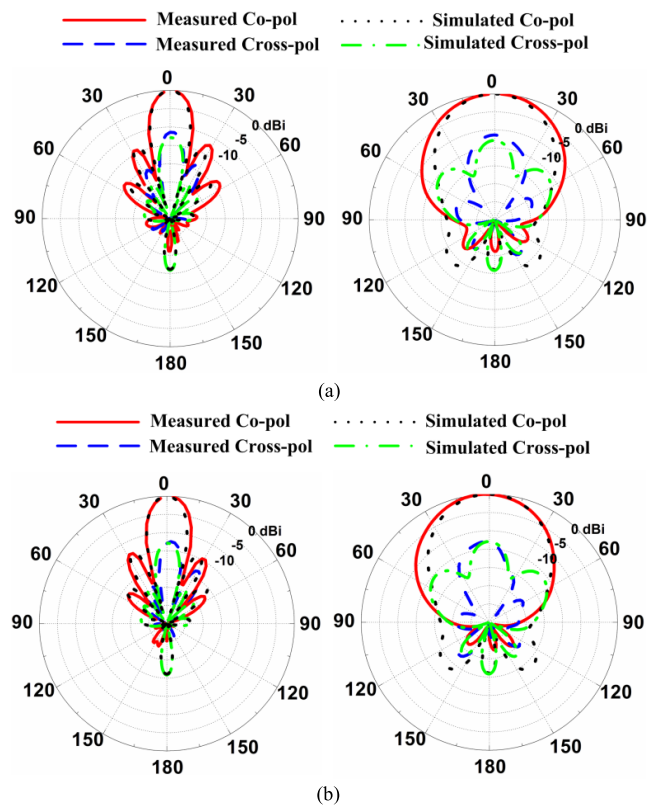


FIGURE 16. (a) Measured and simulated radiation patterns at both horizontal (left:  $\varphi = 0^\circ$ ) and vertical (right:  $\varphi = 90^\circ$ ) planes at 2.3 GHz for  $+45^\circ$  mode. (b) Measured and simulated radiation patterns at both horizontal (left:  $\varphi = 0^\circ$ ) and vertical (right:  $\varphi = 90^\circ$ ) planes at 2.3 GHz for  $-45^\circ$  mode.

radiation patterns. It can be used as base station antenna for WLAN or RFID systems.

## V. CONCLUSION

A  $\pm 45^\circ$  polarization reconfigurable aperture-fed patch antenna array has been investigated. A new technique to realize the reconfigurable  $\pm 45^\circ$  linear polarizations has been proposed which introduces RF switches on the cross aperture to excite a square patch antenna to switch the polarizations. This technique is practical to develop a polarization reconfigurable antenna array. The design concept has been studied and the antenna array prototype has been fabricated and tested. The measured results show our proposed antenna successfully realizes the reconfigurable  $\pm 45^\circ$  polarizations with high gain and desired radiation pattern, which is the first design validated by experiment among other designs as discussed in Part I.

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