

RESEARCH PAPER

A design of ring-shaped dual-band/ multi-band circularly polarized microstrip antenna based on slots mutual coupling

FARZAD ALIZADEH, CHANGIZ GHOBADI, JAVAD NOURINIA, MAHDI DADASHI AND RAHIM BARZEGARI

A new approach for designing a single-feed circular microstrip antenna with dual-band/multi-band circularly polarized (CP) radiation are demonstrated and studied experimentally. It is presented that by embedding pairs of asymmetrical ring-shaped arc slots to the boundary of both circular patch and the ground plane the impedance bandwidth of the antenna increases. This can be achieved by making use of both mutual coupling between the resonances of the ring-shaped arc slots and the fundamental resonances of the circular antenna. Also, by extending the ring-shaped arc slots out with narrow slots, the circular microstrip patch antenna can perform dual-band/multi-band CP radiation. Further details of the proposed CP microstrip antenna designs are described, and typical experimental results are presented and discussed.

Keywords: Antennas and propagation for wireless systems, Antenna design, Modeling and measurements

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I. INTRODUCTION

Circularly polarized (CP) antennas can receive all kinds of electromagnetic waves due to the insensitivity of the polarization matching between the transmitter and receiver. In this basis, the CP antennas have been applied to numerous wireless communication networks. Recently, the development of modern wireless communication systems has been brought greater interest in compact dual-band/multi-band CP applications [1]. For example, single or dual-feed stacked patch antennas are reported to have dual-band/multi-band CP properties with a good impedance and AR bandwidth, [1, 2] at the expense of the height and cost. In [3], a single-feed multilayer CP microstrip antenna with S-shaped patch with dual-band CP operation is introduced for GPS applications. The slotted ground plane CP antennas for their advantages, like compactness and improvement in gain and axial ratio bandwidth are also studied widely [4, 5]. Single-feed single-layer slot loaded microstrip antennas are reported to have dual-band applications [6–9]. However, their impedance bandwidth is narrow which it is an inherent problem of microstrip antennas. For compensating this problem, two pairs of asymmetric ring-slots embedded on the ground plane are introduced for a single-band CP microstrip antenna [10]. The possibility of achieving a compact CP microstrip antenna based on arc-shaped slots is also investigated [11]. Some novel techniques are also included in

literature for achieving circular polarization characteristics [12, 13]. In [14], by merging and combining the near resonances of the half wavelength off-set parallel striplines a wider bandwidth is achieved based on mutual coupling for a phase-reversal antenna. In addition, it is possible to increase the bandwidth or enhance the properties of this technique with adding some dummy slots to the parallel off-set slots [15]. This letter introduces a single-feed single-layer dual-band antenna for 1.5/2.5 GHz and a triple-band antenna for 1.02/1.36/1.43 GHz. The antenna design for each operation exploits the previously mentioned slot-loaded technique on the ground and also utilizes the complementary concept of the novel bandwidth enhancement technique which is stated earlier in this section. To demonstrate these concepts, the proposed dual-band CP antenna is designed and a parametric study was carried out. The antenna is simulated by high frequency structure simulator (HFSS) and time domain CST Microwave studio, then the performance is verified by the measurements.

II. ANTENNA GEOMETRY AND DESIGN

The proposed antenna designs for impedance bandwidth enhancing and compact dual-band/multi-band CP are depicted in Fig. 1. Figure 1(a) relates to the main antenna is composed of two printed metallic circular elements as ground plane and radiating patch where two pairs of asymmetric ring-shaped arc slots, with a narrow width w , are embedded on each side. The main antenna is fabricated on a low cost FR4 with $\epsilon_r = 4.4$, a loss tangent of 0.02 and

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a thickness of $h = 1.6$ mm. The antenna fed by a 50Ω coaxial probe where the impedance matching is achieved by changing the ring slots width (w) and gap (g). The overall size of the structure is $L_{sub} \times W_{sub}$ mm². Figure 1(a) exhibits the asymmetric ring-shaped arc slotted circular patch and ground plane with radius of r and R , respectively. The two asymmetric arc pairs are first centered to the reference point of the circular patch, then defined by a width of w and radius of r_1 and r_2 , respectively, can be described as outer and inner ring-shaped arc slot radius. Finally, each arc, as depicted, is delimited by a gap of width g . The same configuration is exactly mirrored to the ground plane to take the advantage of mutual coupling to increase the bandwidth of a simple microstrip antenna. Using symmetric pairs of arc-shaped slots dictates a dual frequency operation with almost same radiation patterns and by adjusting them both $TM_{1,1}$ and $TM_{1,2}$ modes of circular patch can be excited properly. Also, it is reported that if two pairs are used, then, with a few modification of configuration, two orthogonal modes with equal amplitudes and 90° phase difference for CP operation can be excited for the both modes [7]. Another type of same modification is illustrated in Fig. 2(b). As shown, by extending a pair of dummy-slots with length of L_{ds1} and width of w_{ds1} out of the inner arc-shaped slots in the ground plane by an angle of φ , an antenna is proposed for dual-band CP operation. Also note that, these dummy slots can be placed anywhere to reach a CP radiation.

It must be noted that the CP performance in both bands is controllable by optimization the features of these dummy slots. Utilizing the properties of asymmetric ring-shaped arc slots in both metallic plates can be realized when additional tuning slots with different length are etched in each end of an arc pair, as shown in Fig. 1(c). In the same figure, the length of tuning slots that are etched to the outer pair of ring slots, L_{ts1} , must have a common ending point as the tuning slots which are embedded to the inner ring-shaped arc slots, L_{ts2} . So, the length of tuning slots is also related to each other, determined by shifting method as $L_{ts1} = L_{ts2} + 2w$, is discuss in the next section. The antenna of Fig. 1(d) is similar to the previous one but the

dummy slots are extended to modify the bandwidth performance of the antenna.

III. PARAMETRIC STUDY

In order to enhance the impedance bandwidth of a single layer microstrip antenna and achieve a dual-band/multi-band CP operation, a parametric study has been carried out by HFSS software. All other parameters which have not been mentioned throughout this study are assumed to be fixed to the values of Table 1. The simulated return loss for different values of slots of antenna 1 is shown in Fig. 2. In Fig. 2(a), there are four types of resonant frequencies that are shown with arrows. As the amount of gap between the slots is increasing, the lower (f_1) and upper (f_3) resonant modes namely $TM_{1,1}$ and $TM_{1,2}$ are slightly changing as the main properties of the metallic parts remain constant. Meanwhile, the other significant resonant modes between these two frequencies are belong to inner patch radius, $TM_{2,1}$, f_2 around 2 GHz, and the combination of two resonant modes of asymmetric ring-shaped slots, namely f_3 and f_4 . For f_3 , it is obvious that increasing the amount of gap or decreasing length of slot will force it into the upper frequencies. This is also valid for f_4 . As discussed in [15], these modes are related to the coupling and combining of two resonances of each pair which are arranged to couple through a parallel metallic gap between them. The parallel metallic gap can be realized as a shunt capacitance which plays the main role in the mode coupling of two ring-slots. It is clear that the amount of this capacitance is changing due to the parameters of slots which leads to change in the amount of g . The coupling concept is completely explained in the corresponding reference [15] and only the results are exploited here. It can be observed from Figs 2(a) and 2(b) that by proper selecting the values of g and w the impedance bandwidth of the main resonant modes of patch can be extended by merging and packing of more resonant modes around the frequency of interest. In other words, the higher-order mode of patch is fixed while the resonant

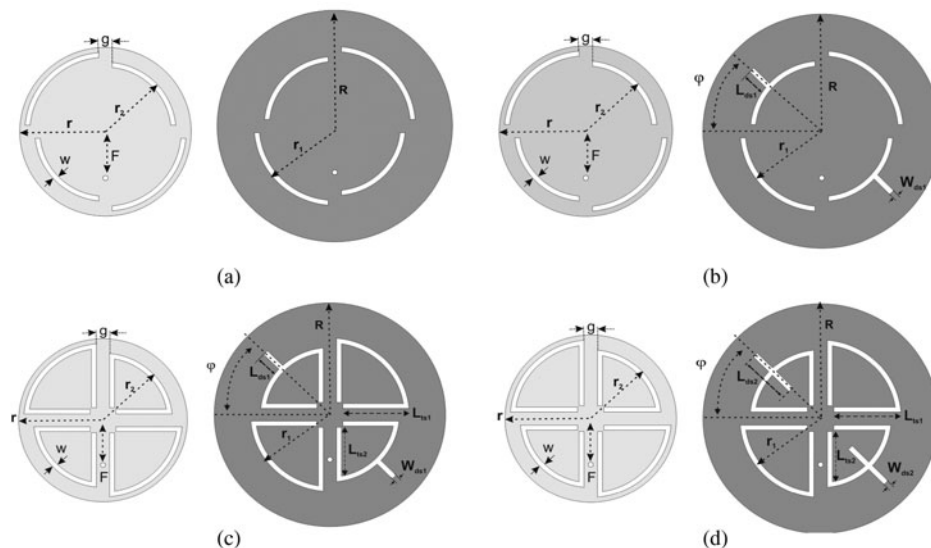


Fig. 1. Proposed asymmetric arc-shaped slot microstrip antennas for enhancing impedance bandwidth and dual/multi-band CP operation (a) antenna 1, (b) antenna 2, (c) antenna 3, and (d) antenna 4. Patch in lighter color on the top of substrate integrated with ground-plane in darker color placed at bottom.

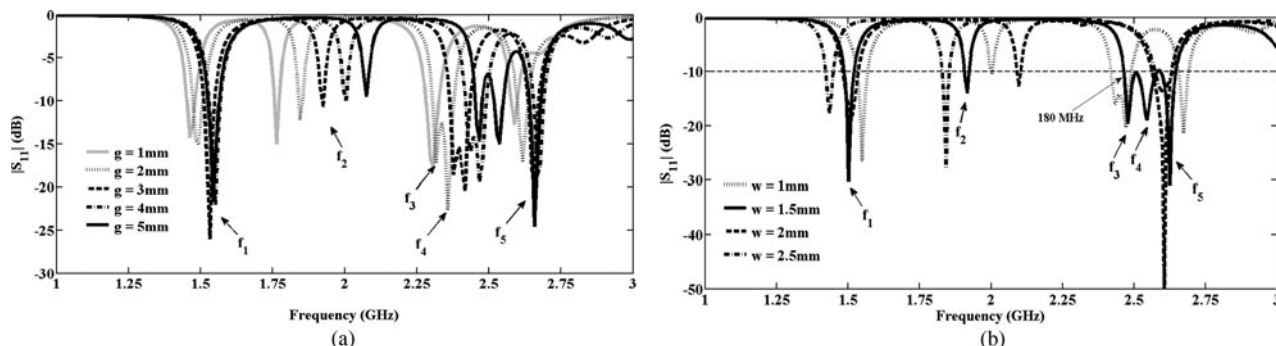


Fig. 2. Simulated $|S_{11}|$ versus frequency for the stated values of Fig. 1(a): (a) for various slots gap (g), (b) for various slot widths (w).

Table 1. Optimized dimensions of the antennas of Fig. 1.

Parameter	Dimension (mm)	Parameter	Dimension (mm)	Parameter	Dimension	Parameter	Dimension (mm)
L_{sub}	70	R	35	r_1	24 mm	W_{ds1}	1.6
W_{sub}	70	r	25.5	r_2	21 mm	L_{ds1}	6.5
W_{ds2}	1.6	F	14	φ	45°	L_{ts1}	18.5
L_{ds2}	15	g	4	w	1.5 mm	L_{ts2}	15.5

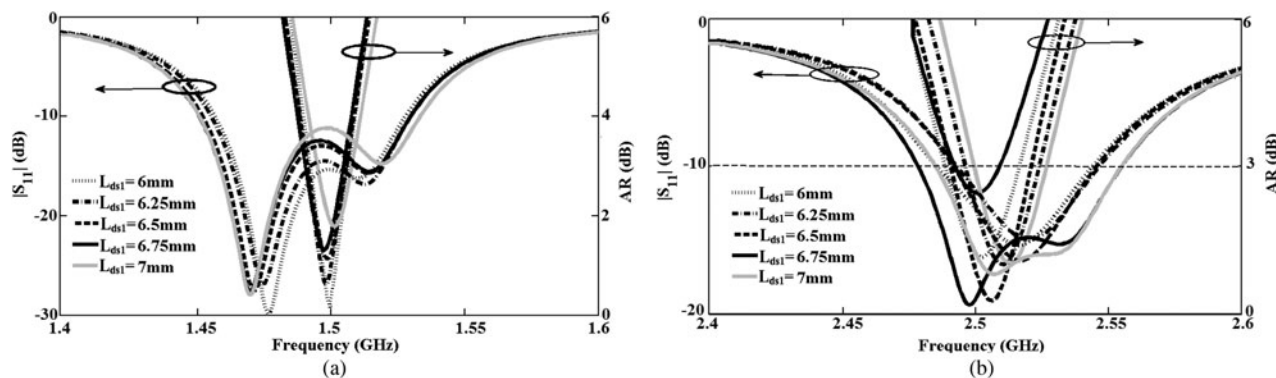


Fig. 3. Simulated $|S_{11}|$ and axial ratio versus frequency for the stated values of Fig. 1(b): (a) lower band (b) upper band.

modes of the slots are shifting toward this frequency. That is because the slots in the both plates have different length which leads to a complementary model of the prior one. This concept is fully utilized in the designs of the antenna 2 and 3 for increasing the bandwidth or achieving a multi-band CP operation in the lower band. It has been done by moving these resonances to the lower frequencies and couple_combine them with the fundamental resonant mode of the circular patch (f_1). Figures 3(a) and 3(b) show the effect of the length of dummy slots on the reflection coefficient and 3 dB axial ratio of the antenna 2 at the boresight. It is mentioned that the fundamental and the higher order mode of the circular patch are very important to form a dual-frequency operation and so as for a circular polarization. This extra pair of dummy slots changes the current distribution in the ground plane of the antenna at 1.5 and 2.5 GHz for antenna 2. Figures 4(a) and 4(b) show the current distribution around the patch and ground plane. As shown, the strongest current distribution is dispersed widely around the edges of the asymmetric arc-shaped slots in both bands, which can cause the meandering of the current paths on the patch or ground plane. However, it can be seen from Fig. 4(a) that

the current flows a longer path near the edges and engages both inner and outer slots. On the other hand, the current flow is restricted around each slot in the upper band, as shown in Fig. 4(b). Adding a pair of dummy slots affects the both bands operations and slightly changes the currents length so that they show CP properties. The width (w) and length of tuning slots (L_{ts1} , L_{ts2}) without the effect of dummy slots were studied in Fig. 6(a). It means the tuning slots are directly added to the antenna 1. It was observed that by shifting the upper combined resonant modes toward the fundamental frequency the impedance bandwidth of the antenna increased. Also, it was found that other resonant frequencies appear around 1 GHz which are related to the current flow in the both inner parts and outer parts of the patch. This slots due to their symmetry form a CP radiation at around 1 GHz, as shown in Fig. 6(b). The reflection coefficient and 3 dB axial ratio of the antenna 3 with variation of dummy slots at 1.35 and 1.43 GHz are shown in Fig. 6(c). Figure 5 describes the current distribution of the antenna 3 at minimum axial ratio of each band. As shown, all the slots are charged and discharged repeatedly due to their length in a period of time so that the antenna always provides the 90

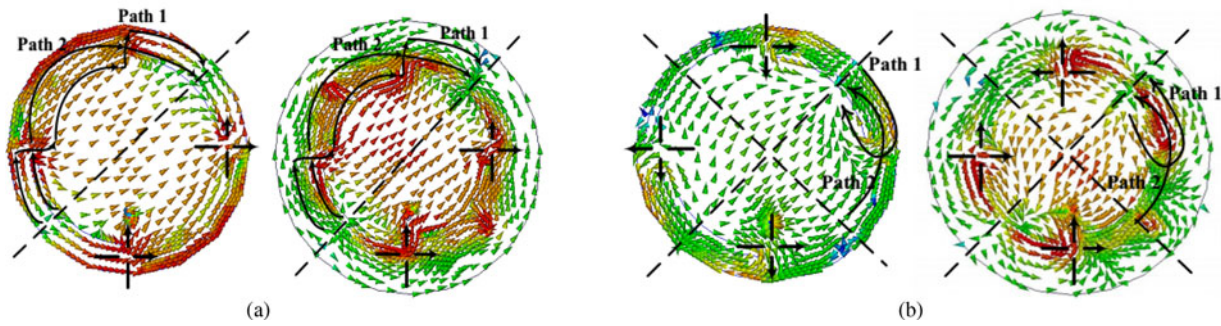


Fig. 4. Current distributions of antenna 2 at (a) 1.5 GHz and (b) 2.5 GHz.

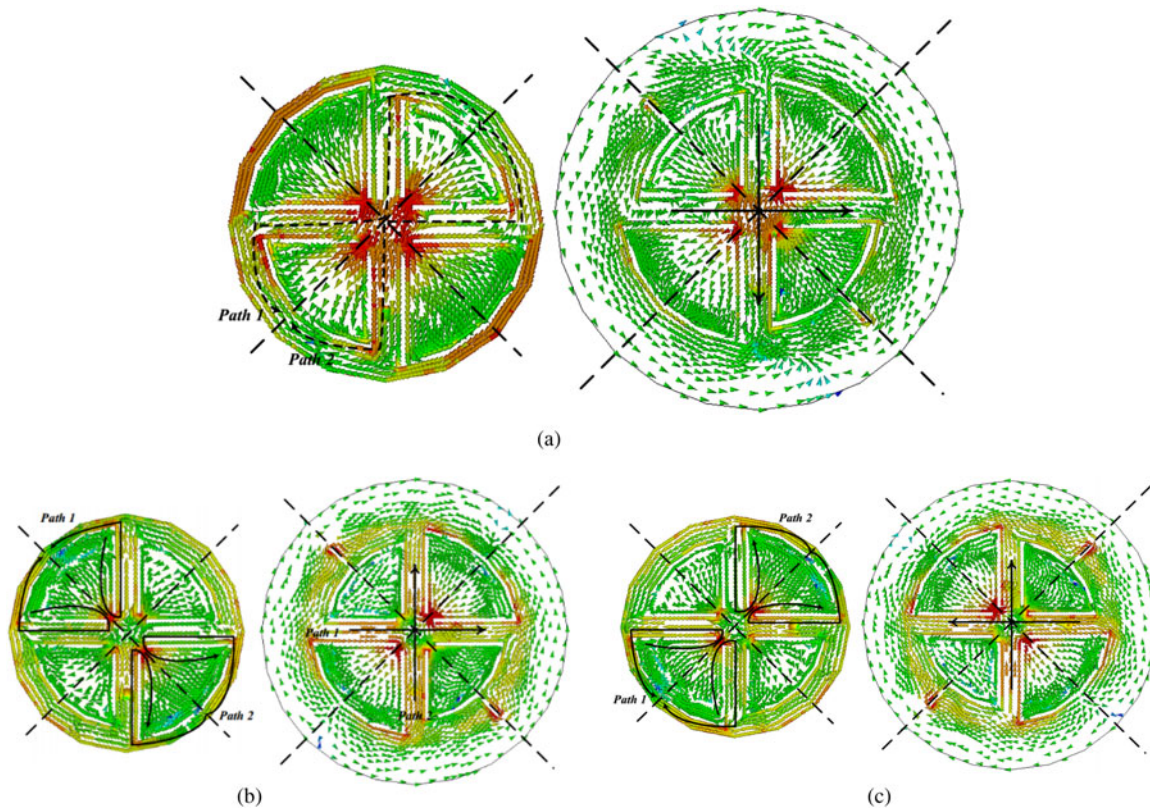


Fig. 5. Current distributions of antenna 3 at (a) 1.02 GHz, (b) 1.36 GHz, and (c) 1.43 GHz.

phase difference which confirms the inherently CP property of antenna 3 in the mentioned frequency bands. Design guidelines based on the simulation procedure is suggested as follows:

- (1) The initial dimensions of the circular patch must be determined to operate in the desired frequencies, λ_1 and λ_5 .
- (2) Asymmetric ring-shaped slots lengths must be optimized to resonance between two frequencies of the patch. Length of each asymmetric ring-shaped slot is close to $\lambda_5/4$ when they embedded to the boundary of the patch where λ_5 , the wavelength of upper resonance in free space is represented in Fig. 2. So, each asymmetric slot can help to meandering the path of current on the patch and forming a CP radiation, as shown in Fig. 4(b).
- (3) For forming second CP radiation, a pair of dummy slots should be add to the slots with shorter length to be

equal in length with the slots with longer length. Note that with adding dummy slots the sum of two ring-shaped slots will be equal to $\lambda_1/4$.

- (4) Tuning slots (L_{ts1} , L_{ts2}) must be embedded on the patch and connected to the asymmetric ring-shaped slots. Adjust the length of ring-shaped slots with tuning slots to resonance in frequency lower or equal to the lower frequency of the patch, f_1 . Apply the same design principle to the ground plane.
- (5) Adjust the CP characterizes of the antenna with changing dummy slots to the form represented in Fig. 1(d). Make sure that both 3-dB AR bandwidth of around f_1 falls totally within the -10 dB return loss bandwidth.
- (6) Check the possibility of forming a CP radiation in resonances lower than the first frequency of the patch. Optimize the overall structure and specially the tuning slots to reach a multi band function near 1 GHz.

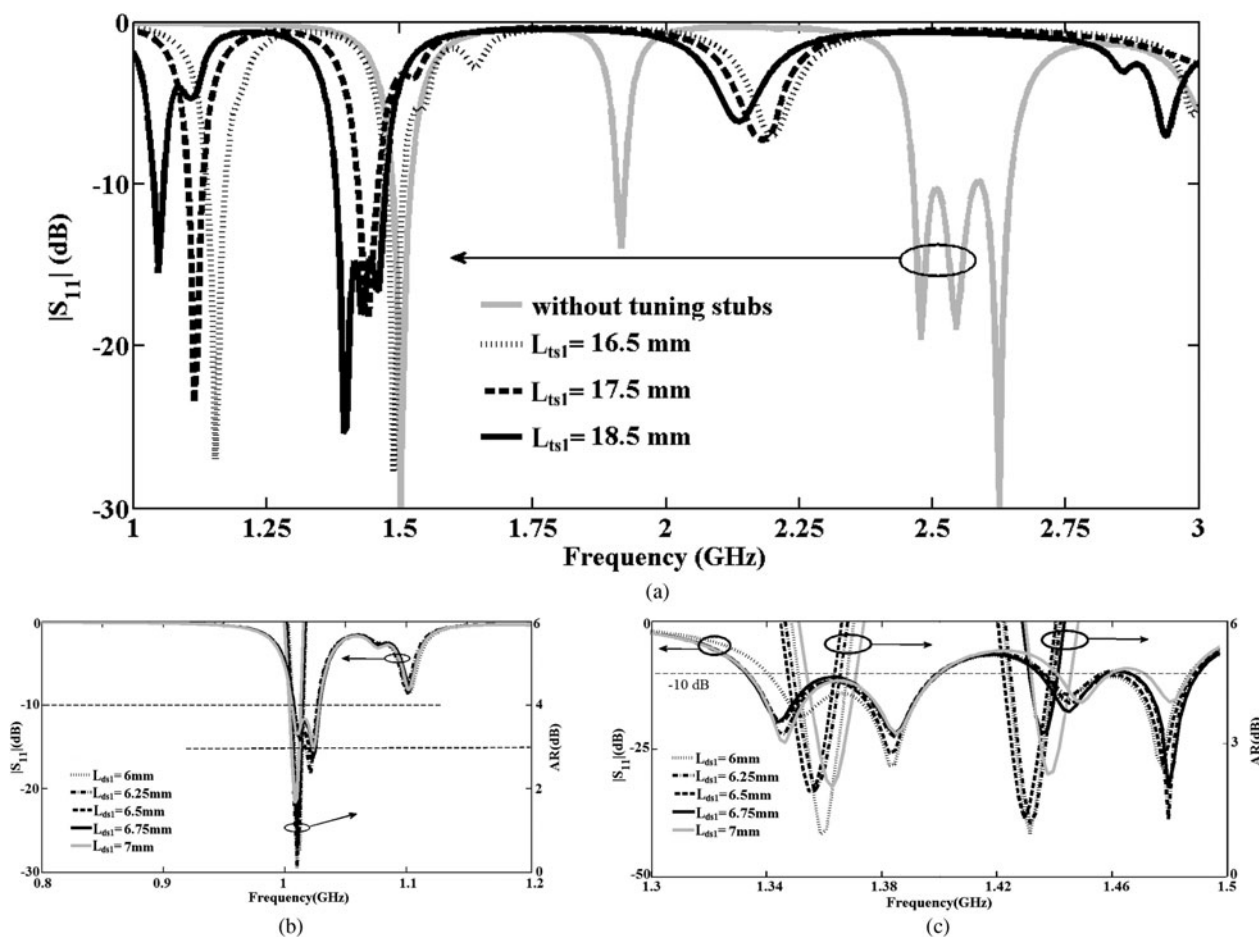


Fig. 6. Simulated $|S_{11}|$ (a) without dummy slots for antenna 3, (b) with dummy slots at 1.02 GHz, and (c) with dummy slots at 1.36 and 1.43 GHz. Axial ratio is also included in (b) and (c).

IV. EXPERIMENTAL RESULTS

Experimental results for each antenna have been carried out to demonstrate the performance of the designs. The photograph of top view and bottom view of each fabricated antenna and a comparison between measured and simulated return loss of the antennas plus their 3-dB AR measured at the boresight direction are shown in Fig. 7. The impedance bandwidth is measured with Agilent E8363C PNA network analyzer and axial ratio, gain and patterns of the experimental antennas were measured in our anechoic chamber in the laboratory building with a signal generator, antenna rotator and LG SA-970 spectrum analyzer. A frequency shift between the simulated and measured values is observed which is mainly caused by fabrication inaccuracy or soldering process. Figure 7(a) shows the measured and simulated return loss of antenna 1. The axial ratios of antennas were measured in boresight direction and at the centre resonant frequencies where the minimum axial ratio was obtained. As shown in Fig. 7(b), the measured impedance bandwidth and axial-ratio at the boresight direction of the antenna 2 are about 80, 30 MHz at the lower band and 100, 40 MHz at the upper band, respectively. The measured impedance bandwidth and axial-ratio at boresight direction of the antenna 3 which are shown in Fig. 7(c) are about 30, 8 MHz at the lowest band (around 1 GHz) and 90, 10 MHz around 1.39 GHz and 80, 10 MHz at the upper band (around 1.45 GHz), respectively.

As shown in Fig. 7(d), the two upper bands of antenna 3 (1.36 and 1.43 GHz) are merged and modified into a wider bandwidth so the axial ratio for this antenna is not depicted. Also, the far field parameters of antenna 4 is not included. Figure 8 shows the measured and simulated CP gain at the boresight direction for both antenna 2 and antenna 3. The measured gain of antenna 2 is about 3.8 dBic at the lower band and at the upper band, it is around 3.6 dBic, with a variation of around 0.3 dBic within 3-dB AR for both bands. The measured CP gain of antenna 3 is around 2.8 dBic at lowest band and around 3.3 dBic at the upper bands. The simulated radiation patterns at the minimum S_{11} of each band of the antenna 2 with both CST and HFSS software is shown in Figs 9(a) and 9(b). For antenna 2, a boresight CP radiation pattern is observed at the lower band; however, the patterns at the upper band show a 30° off-boresight radiation. This is primarily caused by both the presence of the ring-shaped slots in the configuration which form the CP properties of the antenna 2 and also due to antenna operation near the second resonance of the circular patch. It is found that the asymmetric current distribution of the higher order modes near the outer asymmetric slot causes beam squint and pattern deterioration for the upper band. The normalized simulated radiation patterns of antenna 3 at minimum axial ratio of each band are exhibited in Fig. 10. It can be seen from Fig. 10 that the radiation pattern of the antenna 3 is modified owing to the performance of antenna near the first-order modes of the antenna. The

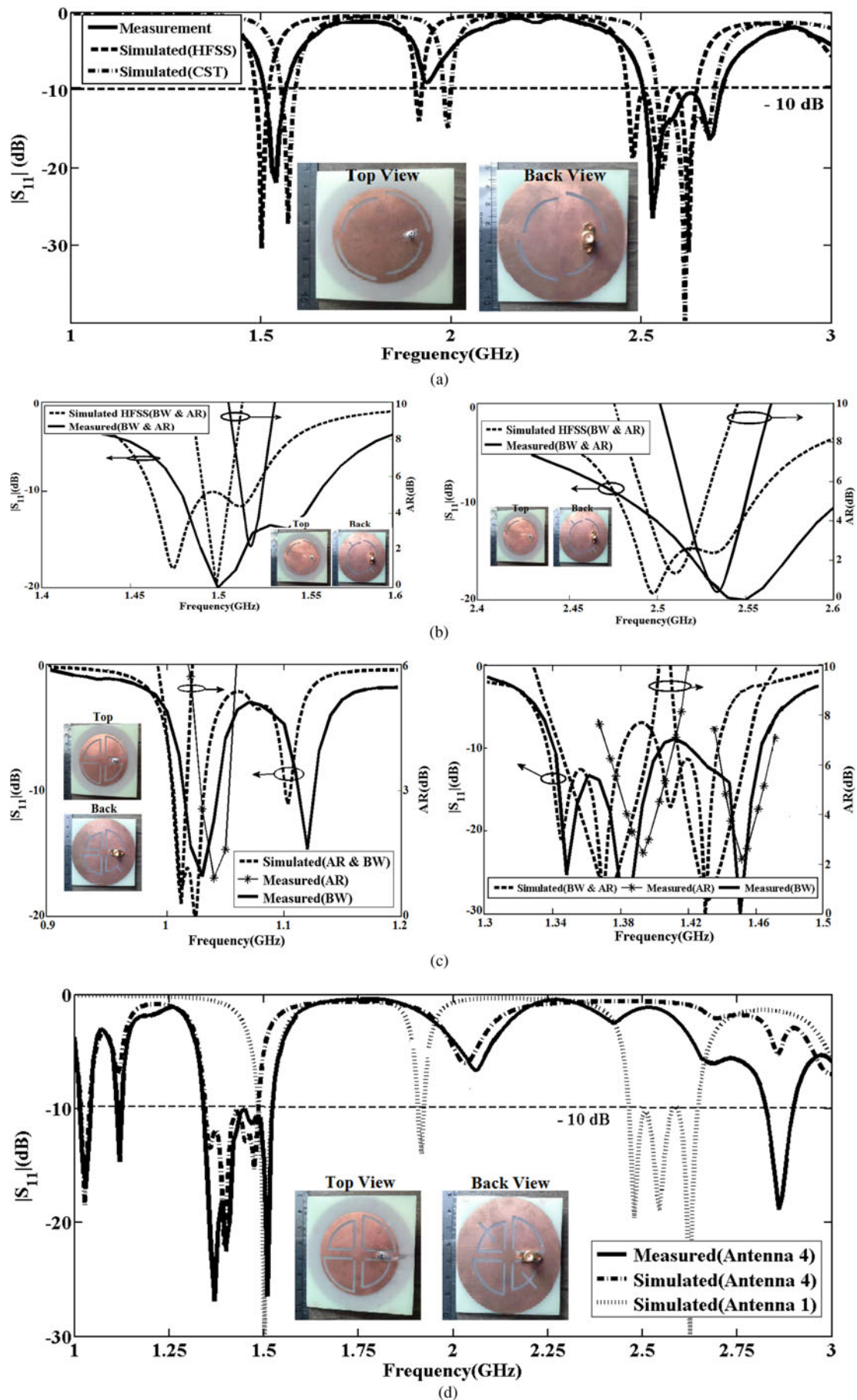


Fig. 7. Photographs of the top and back view of the prototypes: (a) antenna 1, (b) antenna 2, (c) antenna 3, and (d) antenna 4.

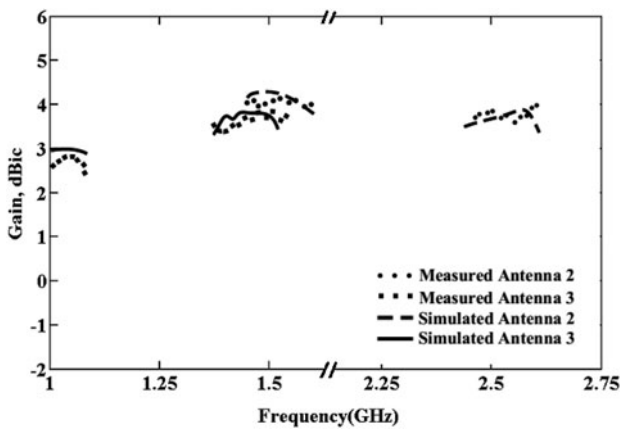


Fig. 8. Measured and simulated gain of antenna 2 and antenna 3 at the boresight.

current distribution is mainly flow in the inner parts of the patch while in antenna 2 the current is distributed between the asymmetric slots and outer edge of the patch. The measured radiation patterns for the antenna 2 at 1.5 and 2.5 GHz are plotted in Figs. 11(a) and 11(b) and for antenna 3 at around 1, 1.39, and 1.45 GHz are depicted in Figs. 12(a)–12(c), respectively for both *xz* and *yz* planes.

V. CONCLUSION

A dual-band/multi-band single-feed single-layer CP microstrip antenna has been proposed, designed, fabricated, and tested. In contrast to previously reported dual-band/multi-band CP antennas, this letter introduces a new and simple design for dual-band/multi-band antenna by taking the advantage of the mutual coupling between ring-shaped slots to both enhance the impedance bandwidth and also draw the upper CP frequency to near the lower one. The other

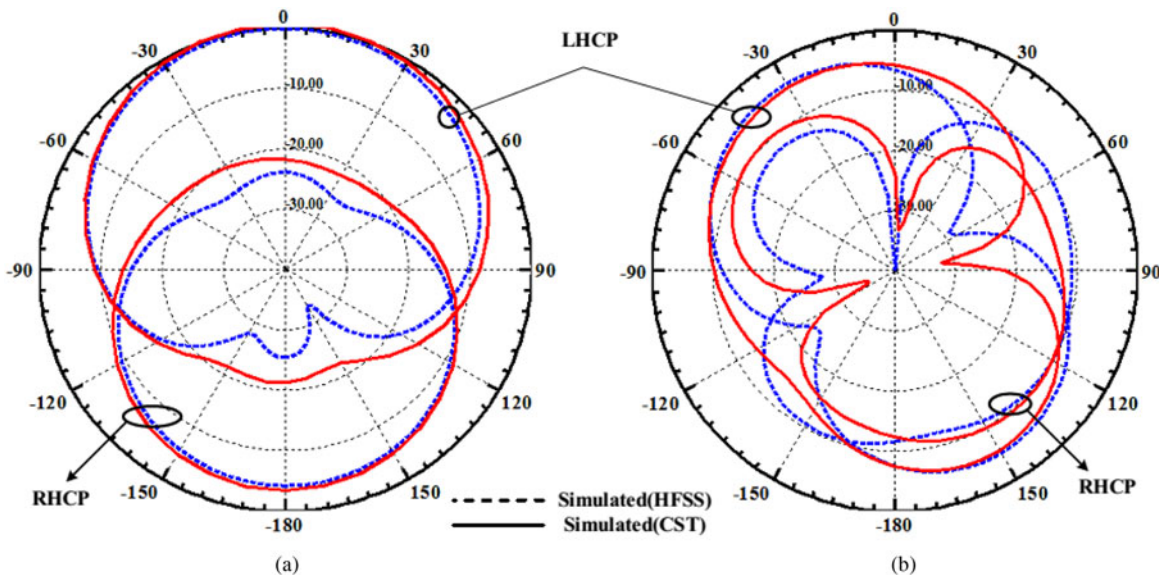


Fig. 9. Simulated radiation patterns of the antenna 2; (a) lower band (left), (b) upper band (right). The scale is 10 dB per division.

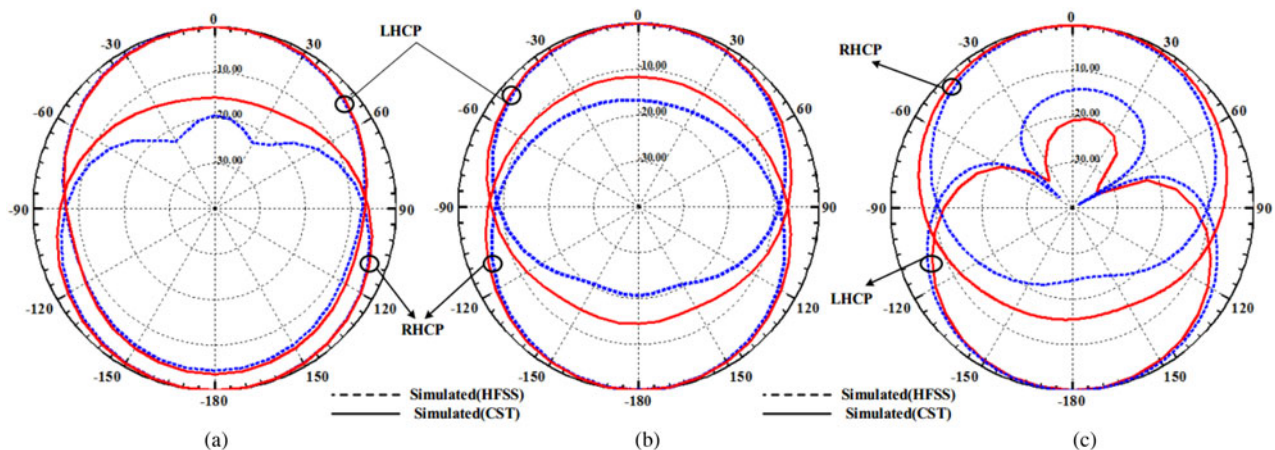


Fig. 10. Normalized simulated radiation patterns of the antenna 3 at: (a) 1.02 GHz (left), (b) 1.36 GHz (centre), and (c) 1.43 GHz (right). The scale is 10 dB per division.

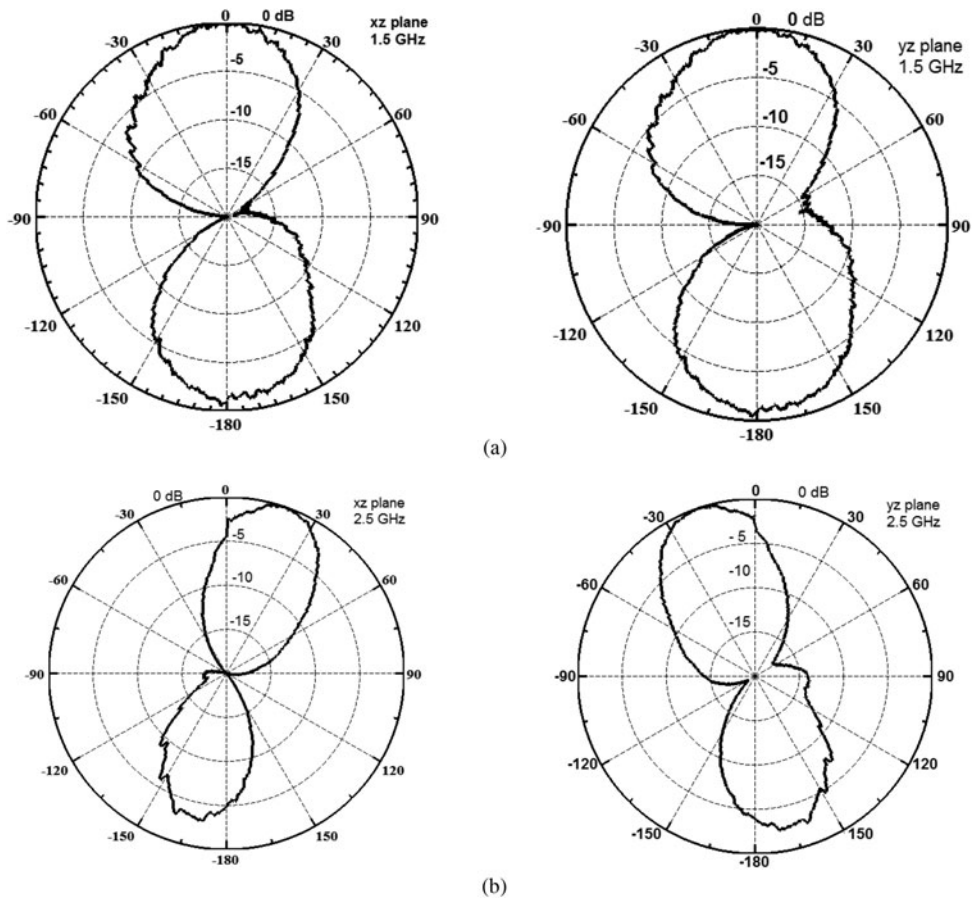


Fig. 11. Measured radiation patterns of the antenna 2; (a) at 1.5 GHz and (b) at 2.5 GHz.

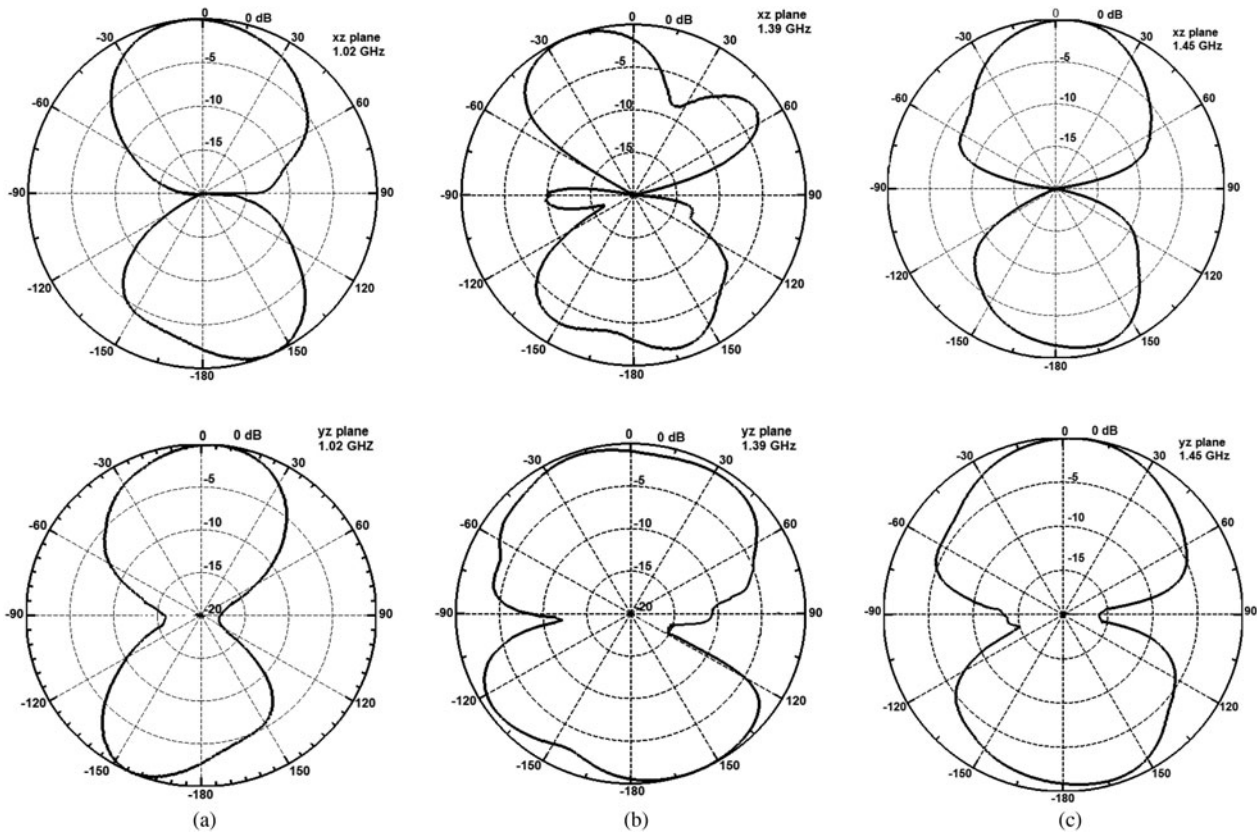


Fig. 12. Normalized measured radiation patterns of the antenna 3; (a) at around 1 GHz, (b) at 1.39 GHz, and (c) at 1.45 GHz.

advantage of this new design in comparison to the other designs with same configuration is the simplicity of fabrication, wider impedance bandwidth in the upper band and later in the lower band, dual-sense CP capability and similar radiation patterns for the mentioned bands. The antennas configuration for each design have been implemented and tested separately.

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