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Broadband Circularly Polarized Stacked Patch Antenna for Universal UHF RFID Applications

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SUMMARY A double layer stacked patch antenna with a size of $200 \times 200 \times 48\,\text{mm}^3$ is proposed in this investigation. To achieve a broad CP bandwidth that can cover universal UHF RFID applications (840–960 MHz), a slot loaded circular patch antenna fed by an L-shaped probe is designed as the lower layer (main patch), while the top layer (parasitic patch) is a simple circular patch loaded with a cross-slot of dissimilar arm lengths. Besides demonstrating a broad 10-dB return loss bandwidth of 16% (823–966 MHz) and a CP bandwidth (3-dB axial ratio) of 14.0% (837–963 MHz), the proposed antenna also yields maximum gain and minimum radiation efficiency of 8.8 dBic and 85%, respectively, across the universal UHF RFID bands.

key words: *circular polarization, patch antenna, stacked patch, universal UHF RFID*

1. Introduction

Presently, one of the methods to develop a CP reader antenna for RFID (Radio Frequency Identification) UHF (Ultrahigh Frequency) is to employ a single probe-fed layer square patch antenna embedded with multiple slits or slots [1], [2]. However, such CP antenna designs have exhibited peak gains of less than 4 dBic, and their 3-dB axial ratio (AR) bandwidth (or CP bandwidth) is usually less than 10 MHz (or 1%). Therefore, such narrow CP bandwidth designs cannot cover the RFID UHF spectrum (902–928 MHz) that is used in North-South America and in most countries, not to mention the universal UHF RFID spectrum (840–960 MHz).

Thus, a number of broadband CP antennas with top loading design (stacked patch) for UHF RFID applications have been investigated [3]–[10]. To excite broad CP bandwidth for UHF RFID readers, the technique of applying a stacked annular-ring microstrip antenna with integrated feeding network has been reported [3]. Although this double-stacked design has demonstrated a low profile characteristic ($220 \times 220 \times 11\,\text{mm}^3$) and a high gain of 8.9 dBic, the measured CP bandwidth was only 6% (893–948 MHz). Thus, a low profile double-stacked antenna with compact planar size ($220 \times 220 \times 11\,\text{mm}^3$) was studied [4], in which a wide CP bandwidth of 11.6% can be achieved by double shorting four sequential rotating stacked patches. However, a complicated feeding-network is required in this design. Furthermore, the designs reported in [3], [4] cannot satisfy the universal UHF RFID spectrum (840–960 MHz).

To achieve a wider CP bandwidth of more than 13.33%, so that the entire universal UHF RFID spectrum (840–960 MHz) can be utilized, antenna designs with meticulously devised single layer feed-structure top loaded by another two layers of patches (main radiating patch and parasitic patch) have been studied [5]–[8]. Nevertheless, because of their complicated three-layer stacked structures, high production cost is anticipated. Hence, directly-fed single-layer wide CP bandwidth antenna designs with L–shaped ground have been investigated recently [9], [10]. In [9], a large parasitic patch was loaded besides the main truncated corner square patch to enhance the CP bandwidth to 14% (837–963 MHz). As for the work in [10], a similar truncated corner patch design was applied; and instead of using a parasitic patch, three slits of unequal length were loaded into the truncated square patch to excite an additional CP frequency, so that a wider CP bandwidth of 16.5% (836–960 MHz) with a high gain of 8.6 dBic can be achieved. Notably, all these reported antenna designs have shown a large planar size of $250 \times 250\,\text{mm}^2$.

In this paper, two slot loaded CP circular patch antennas have been designed and stacked together. Here, the bottom layer CP patch antenna design (with hemi-circular slot) fed by an L-shaped probe stemmed from the work reported in [11]. By stacking the top layer CP parasitic patch onto this bottom layer patch, their induced CP (frequency) operating band can be unified and form a broad CP bandwidth of 14.0% (837–963 MHz) that can cover the universal RFID UHF spectrum. As for the main novelty of this proposed work, because the CP frequency excited by the bottom layer patch is independent from the top layer parasitic patch, this proposed stacked CP antenna can be easily constructed without the need to fine tune the bottom layer patch when the top layer parasitic patch is loaded above it. Furthermore, as compared with the antenna designs reported in [3]–[10], this proposed stacked antenna has demonstrated a compact planar size of $200 \times 200\,\text{mm}^2$. The details of the design of the proposed antenna, and typical the simulation and experimental measurements are also presented in this study.

2. Antenna Structure

The configuration and dimensions of the proposed antenna is shown in Fig. 1, and its geometry is not drawn exactly to scale. The proposed antenna is composed of four main el-

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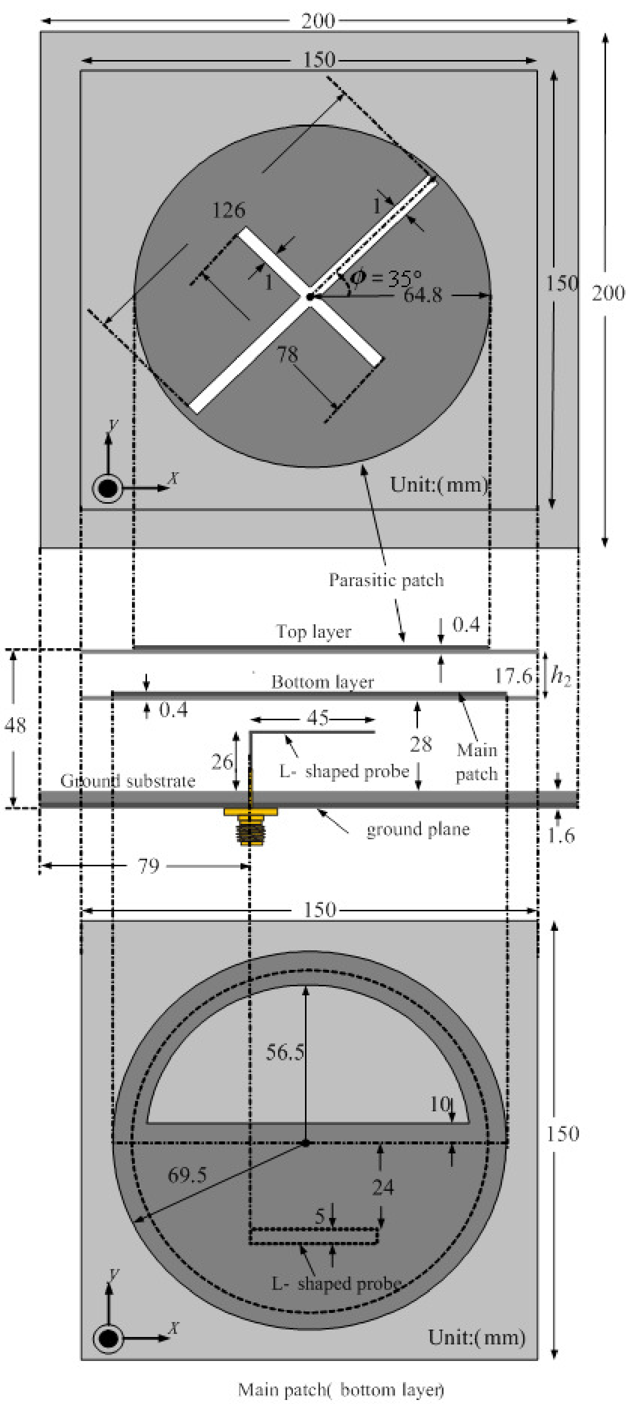

Fig. 1 Geometry of proposed antenna.

ements, namely, the top layer parasitic patch, bottom layer main patch, L-shaped probe, and ground plane. The parasitic patch is a circular patch (with a radius of 64.8 mm) loaded with a cross-slot of dissimilar arm lengths. The main objective of loading this cross-slot is to excite an upper CP frequency at approximately 940 MHz, so that by loading this parasitic patch on top of the main patch, this additionally excited upper CP frequency can be integrated with the lower CP frequency (excited by the main patch) to form a wide CP

Fig. 2 The photo picture of proposed antenna.

bandwidth. As for the main patch that is placed 17.6 mm below the parasitic patch, it is a simple circular patch (with a radius of 69.5 mm) loaded with a hemi-circular slot (with a radius of 56.5 mm). Both the main and parasitic patches are printed on a 0.4 mm thick FR4 substrate (dielectric constant 4.4 and loss tangent 0.02) of size 150 × 150 mm^2.

The L-shaped probe is located 2 mm below the main patch, and it is fabricated by using a 0.2 mm thick copper sheet. It has a width of 5 mm, and is composed of two main sections, namely, the vertical and horizontal sections, and their lengths are 26 mm and 45 mm, respectively. Notably, this L-shaped probe method is applied for achieving good impedance matching. Lastly, the 200 × 200 mm^2 square ground plane is located 28 mm below the main patch, and it is fabricated on a 1.6 mm thick FR4 substrate. The photo picture of the proposed antenna is shown in Fig. 2. In this picture, plastic screws were used to support the top and bottom layer patches above the ground plane.

3. Antenna Designs and Parametric Studies

As mentioned earlier, broad CP bandwidth is achieved because of the combination between two CP stacked patches that can excite two independent CP frequencies. To validate this statement, Fig. 3 shows the simulated results of the proposed antenna (with and without the top layer parasitic patch). As shown in Fig. 3(a), the 10-dB return loss bandwidth of the proposed antenna is only slightly affected when the parasitic patch is removed. In contrast, as shown in Fig. 3(b), removing the parasitic patch from the proposed antenna (main patch only) will result in exhibiting only one CP frequency at 0.86 GHz (with the lowest AR value), and its corresponding CP bandwidth is thus reduced to 3.26% (0.844–0.872 GHz). Notably, stacking the parasitic patch onto the main patch (that forms the proposed antenna) will result in inducing an additional higher CP frequency at 0.94 GHz, which in turn will unify with the lower CP frequency (at 0.85 GHz) and yield a broad CP bandwidth of 14.2% (0.833–0.960 GHz).

To apprehend the effects of loading the cross-slot into the top layer circular parasitic patch, the return loss and AR responses of the proposed antenna with and without loading the cross-slot structure are simulated and shown in Figs. 4(a)

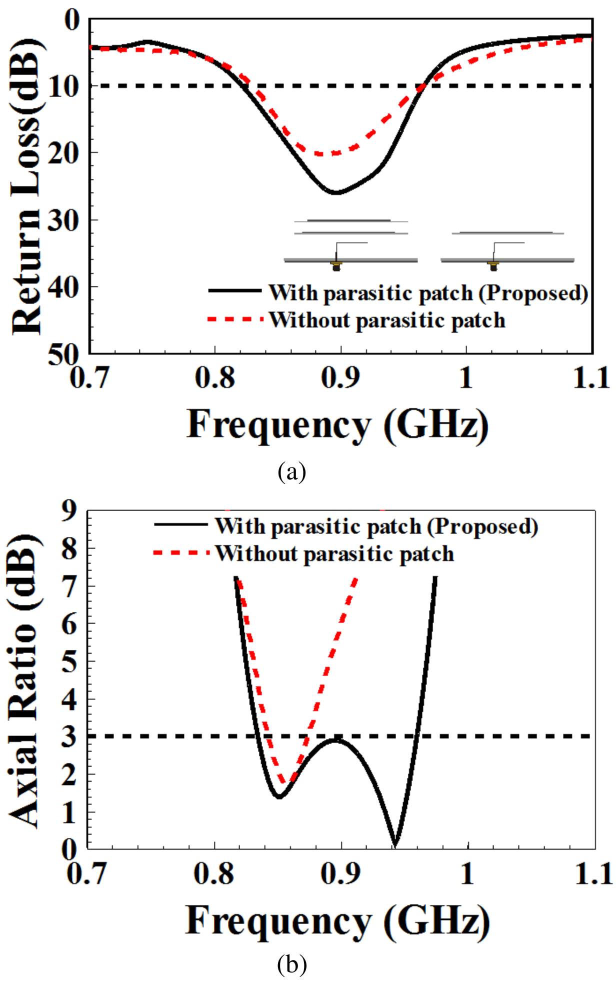

Fig. 3 With and without loading parasitic patch onto the main patch, (a) return loss, (b) axial ratio.

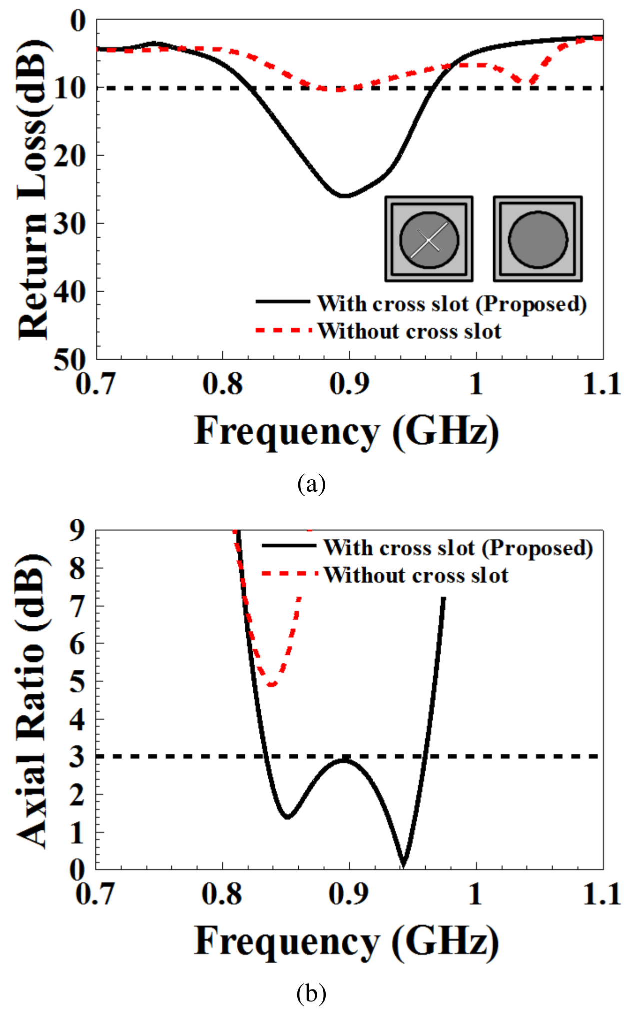

Fig. 4 Proposed antenna with and without loading cross-slot into the top layer parasitic patch, (a) return loss, (b) axial ratio.

and (b), respectively. As shown in Fig. 4(a), poor impedance matching (return loss < 10 dB) can be observed across the bands of interest when the cross-slot is removed from the top layer parasitic patch. From its corresponding AR diagram as shown in Fig. 4(b), besides the missing higher CP frequency, the AR of lower CP frequency (at 0.84 GHz) will also be affected, showing a poor value of 4.8 dB.

To further comprehend these phenomena, the simulated amplitude ratios of the two orthogonal electric fields (E_θ/E_ϕ) and the corresponding phase differences of the proposed antenna (with and without the cross-slot) are plotted in Fig. 5. In this figure, it is obvious that the loading of the cross-slot into the top layer parasitic patch has amplitude ratios (E_θ/E_ϕ) of ±0.1 dB and phase differences of between 70° and 105° within the UHF RFID band (840–960 MHz). Without the cross-slot, poor amplitude ratios (E_θ/E_ϕ) and phase differences of approximately 0.8 dB and 0°, respectively, can be observed especially at 918 MHz. This is because the objective of loading the cross-slot is to perturb the two electric fields so that they are in orthogonal mode and have the same amplitude. Therefore, without loading the cross-slot into the top layer parasitic patch, there will be no CP frequency in the higher frequency band, as shown in Fig. 4(b).

In this study, some of the vital parameters are investigated to determine their optimum impact on the antenna performance. Only one parameter is changed at one time, while the other parameters are kept constant. Commercially available electromagnetic simulator Ansoft HFSS was used to perform the parametric analyses.

3.1 The Effects of Cross-Slotting Angle ϕ

The effects on the return loss and AR of the proposed antenna of varying parameters ϕ from 25° to 45° are shown in Figs. 6(a) and (b), respectively. As depicted in Fig. 6(a), with a step decrease of 5° from ϕ = 45°, it is observed that a 10-dB return loss bandwidth will gradually increase, because the single resonant frequency, initially 900 MHz or so, splits into two modes, especially when ϕ = 25°. These phenomena maybe due to weaker coupling effects between the main patch (with hemi-circular slot) and the parasitic

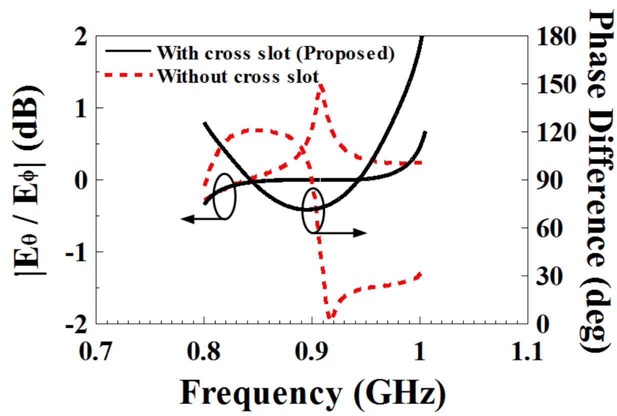

Fig. 5 Simulated orthogonal electric fields (E_θ and E_ϕ) that include amplitude ratio and phase difference diagrams of proposed antenna, with and without loading cross-slot into the top layer parasitic patch.

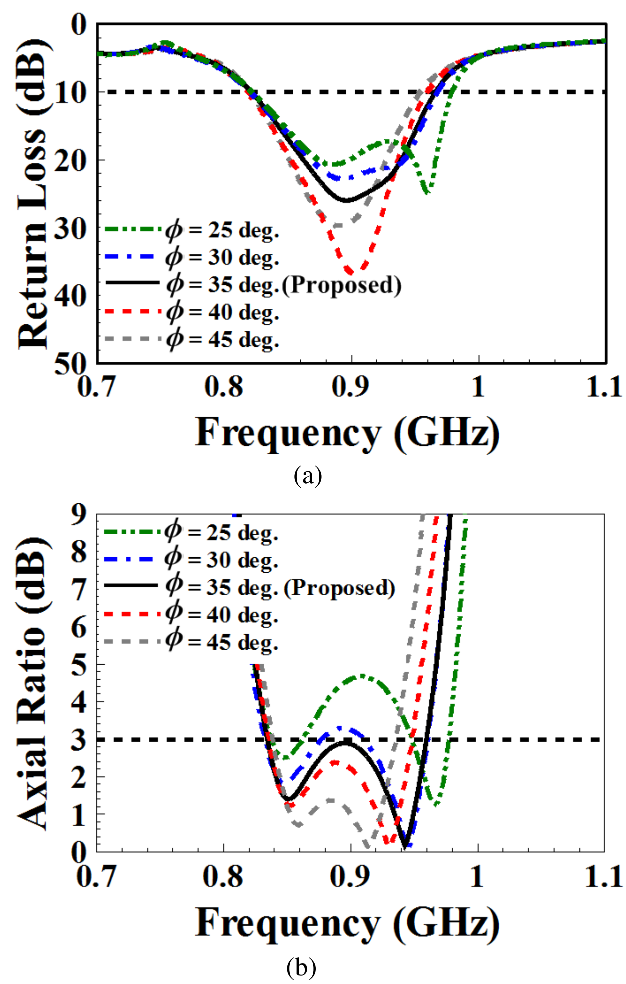

Fig. 6 Parametric analyses for angle ϕ of cross-slot, (a) return loss, (b) axial ratio.

patch (with cross-slot). Due to the splitting of the resonant frequency into two distinct modes that are away from each other at $\phi = 25°$, the lower and upper CP frequencies will also be affected. As shown in Fig. 6(b), when ϕ is decreased to 25°, the two CP frequencies will be farther apart from each other (no longer unified at 3-dB AR threshold), and at the same time, CP performance is degraded (AR value increased). In this case, $\phi = 35°$ is selected as the optimized value in this design, because it offers wider CP bandwidths that can cover the universal UHF RFID applications (840–960 MHz).

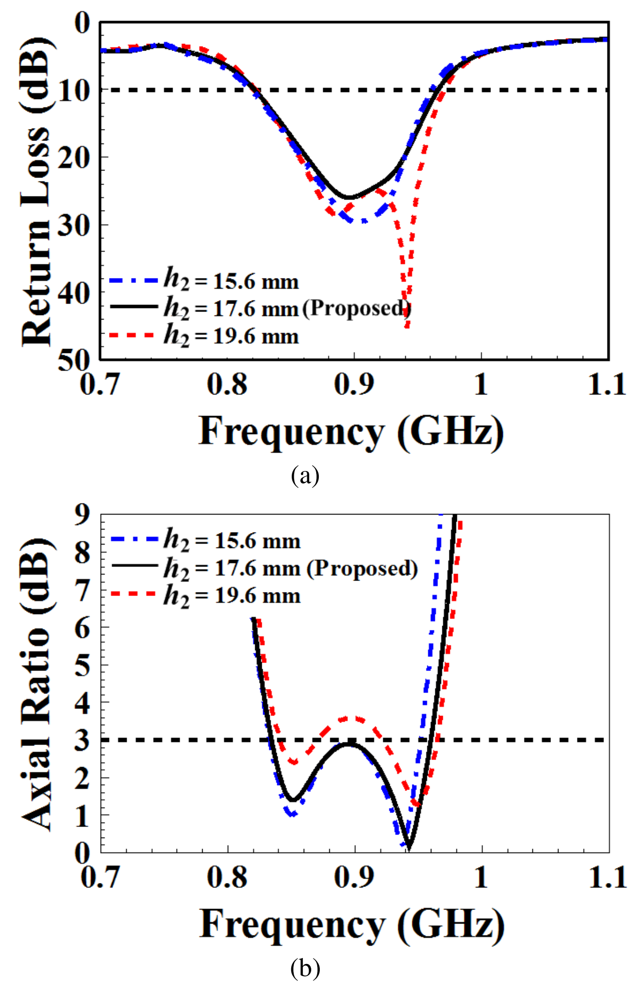

Fig. 7 Parametric analyses for air gap height h_2 between parasitic patch and main patch, (a) return loss, (b) axial ratio.

3.2 The Effects of Air Gap Height h_2

The effects on return loss and AR, by adjusting the air gap height h_2 between the top layer parasitic patch and the bottom layer main patch are shown in Fig. 7. As shown in Fig. 7(a), an increase in h_2 (with a step of 2 mm) from 15.6 mm to 19.6 mm only slightly affects the impedance matching. However, it is noteworthy that at $h_2 = 19.6$ mm, two distinct resonant modes are observed at 880 and 940 MHz. Similar to the phenomena shown in Fig. 6, when $h_2 = 19.6$ mm, two separated (not combined) CP frequency bands are observed in Fig. 7(b). Although the case when $h_2 = 15.6$ mm can give a good combined CP bandwidth, it is no better than the case when h_2 = 17.6 mm. Therefore, h_2 = 17.6 mm is selected as the optimized value in this design.

Figure 8 shows the flow chart of the design and tuning procedure of the proposed CP stacked patch antenna.

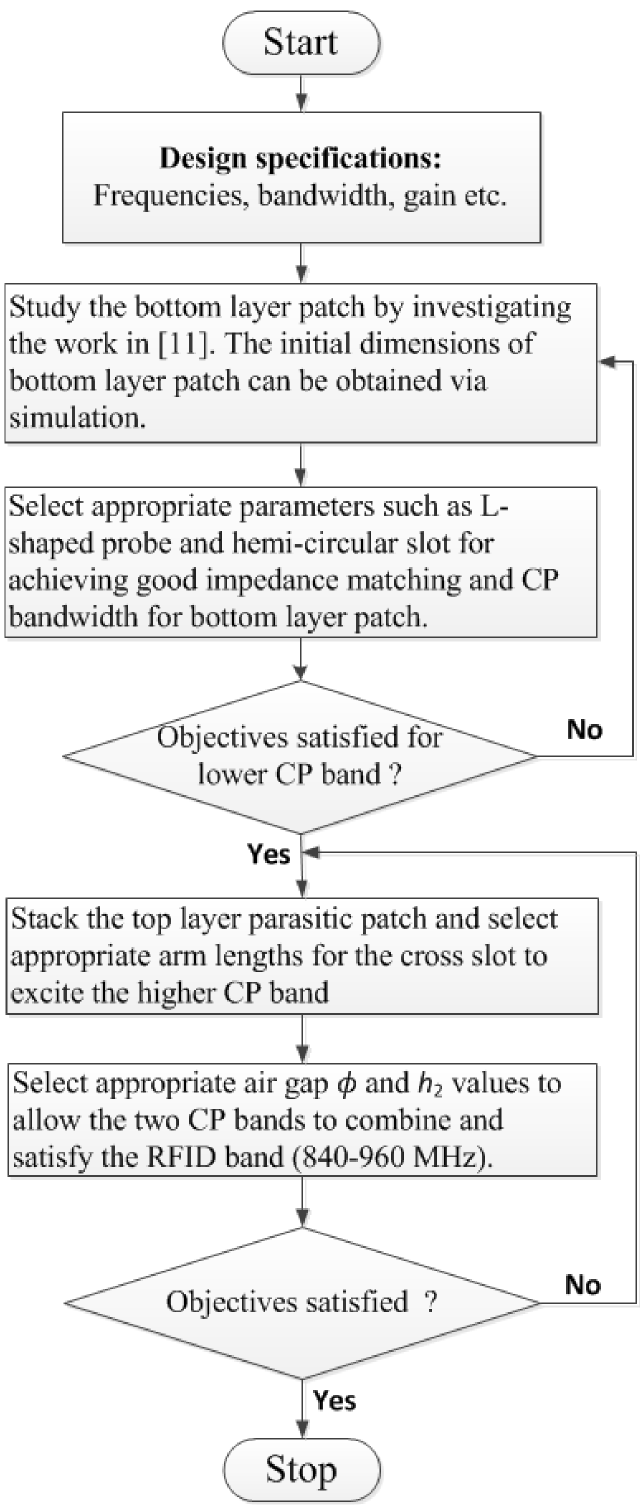

Fig. 8 A flow chart for the design and tuning procedure of proposed CP stacked patch antenna.

The design specifications such as the desired frequency, CP bandwidth (840–960 MHz), and others are first determined. Next, in the work reported in [11], a hemi circular slot loaded CP antenna for (902–928 MHz) UHF RFID applications is studied and applied as the bottom patch layer. By selecting appropriate parameters via simulation, good impedance matching and CP bandwidth can be achieved for the bottom patch layer at approximately 860 MHz (lower CP band), which can be observed in Fig. 3 (proposed without the top layer parasitic patch). After satisfying the lower CP band, the stacked method is then applied to excite the upper CP band. Here, the top layer parasitic patch (with cross-slot) is stacked on the bottom layer patch, and the appropriate cross-slotting angle ϕ and air gap height h_2 are studied. The reasons for loading the cross-slot have already been studied in Figs. 4 and 5, and the effects of ϕ and h_2 have also been investigated in Figs. 6 and 7, respectively. The procedure ends when the two CP bands (lower and upper bands) are successfully combined, and able to satisfy the universal UHF RFID band (840–960 MHz).

4. Results and Discussion

The simulated and measured return losses and AR of the proposed CP stacked patch antenna for universal UHF RFID applications are shown in Figs. 9 and 10, respectively. The measured results are consistent with the simulated ones. As shown in Fig. 9, the measured 10-dB return loss bandwidth was 16.0% (823-966 MHz), and its corresponding CP bandwidth measured in boresight direction was approximately 14.0%, ranging from 837 to 963 MHz, as shown in Fig. 10. Furthermore, at 857 MHz and 949 MHz, minimum AR values of approximately 0.6 dB were also measured. In this case, it is obvious that the CP bandwidth of the proposed antenna can satisfy the universal RFID operating bands.

The radiation patterns, gain level and efficiencies of the proposed antenna were measured in a far-field anechoic chamber (NSI 800F-10/WavePro FFC-700S) for 0.8–18 GHz antenna tests. Figure 11 shows the simulated and

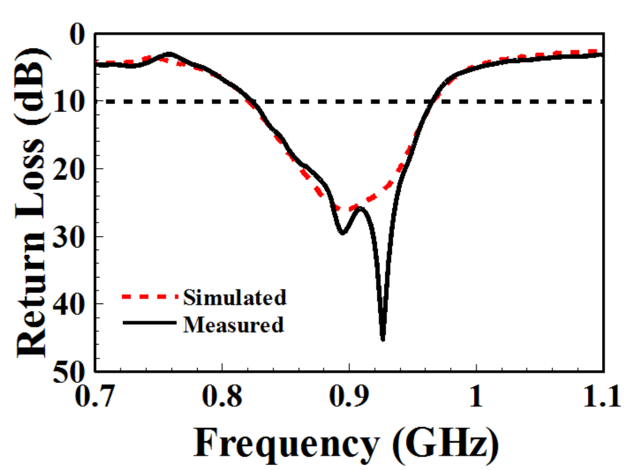

Fig. 9 Simulated and measured return losses.

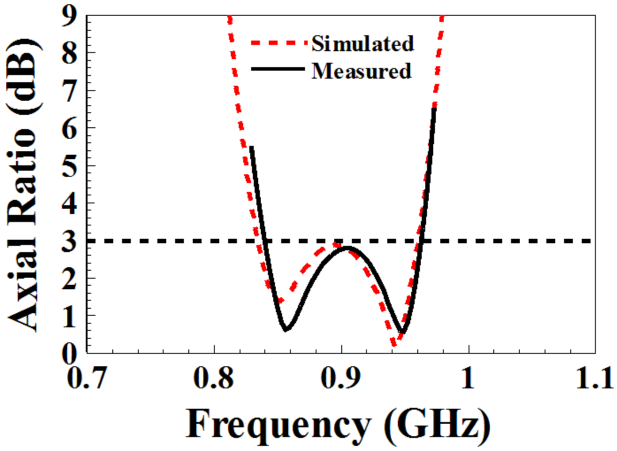

Fig. 10 Simulated and measured axial ratio.

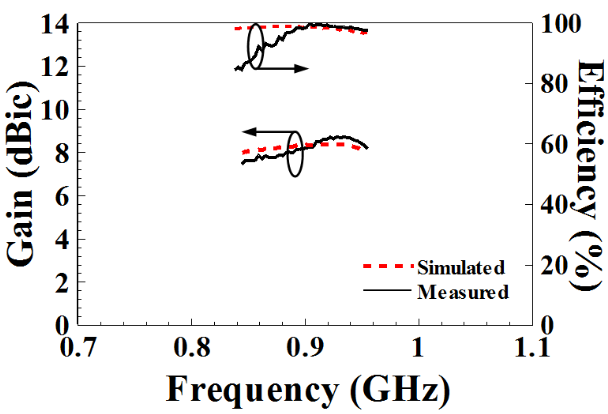

Fig. 11 Simulated and measured gain and efficiency.

measured boresight peak gain levels and radiation efficiencies of the proposed antenna. The measured results are in good agreement with the simulated ones. In this figure, stable gain levels fluctuating between 7.6 and 8.8 dBic were measured across the desired universal UHF RFID bands between 840 and 960 MHz. Furthermore, radiation efficiencies of more than 85% were also measured within the bands of interest. It is noteworthy that slight differences between the measured and simulated results may be due to fabrication error.

Figures 12(a) and (b) show the simulated and measured far-field radiation patterns (normalized) of the proposed antenna in two principal planes ($x-z$ and $y-z$ planes) at 856 MHz and 950 MHz, respectively. The measured results are compatible with the simulated ones. A good broadside pattern with a desirable front to back (F/B) ratio of more than 20 dB was observed in the right-hand CP (RHCP) of both planes. Furthermore, at boresight direction, an acceptable level difference of more than 20 dB was measured between RHCP (co-pol) and LHCP (cross-pol).

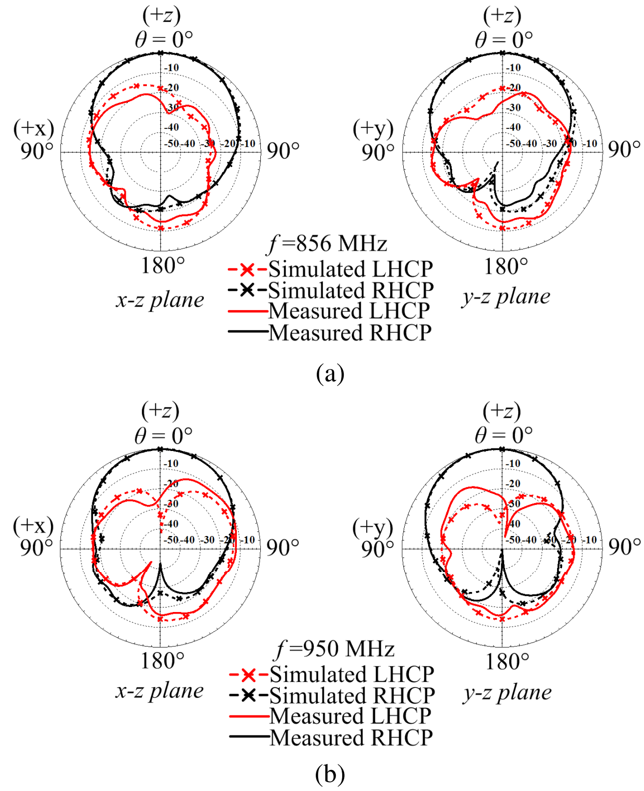

Fig. 12 Normalized simulated and measured radiation patterns at (a) 856 MHz, (b) 950 MHz.

Table 1 Comparison between proposed and reference antennas.

Ants.	Electrical Specification		Mechanical Specification
	CP Frequency (MHz, %)	Max. Gain (dBic)	Size (mm^3)
Ref. [3]	893–948, 6.00	8.9	220×220×11.0
Ref. [4]	871–979, 11.60	4	135×135×13.0
Ref. [5]	818–964, 16.40	8.3	250×250×35.0
Ref. [6]	838–959, 13.50	8.6	250×250×39.5
Ref. [7]	820–980, 17.70	8.0	250×250×20.0
Ref. [8]	816–957, 15.90	9.8	250×250×42.0
Ref. [9]	837–963, 14.00	8.3	250×250×36.0
Ref. [10]	836–986, 16.50	8.6	250×250×60.0
Proposed	837–963, 14.00	8.8	200×200×48.0

5. Comparison of CP RFID Reader Antennas

Table 1 shows the details of the electrical and mechanical performances of the proposed CP stacked patch antenna. Here, eight related reference antennas [3]–[10] for UHF RFID applications are also included in the table for comparison purposes. As shown in this table, even though the CP bandwidth of the proposed one is not as wide as some of the reference ones, it has exhibited enough CP band to cover the entire universal UHF RFID band (840–

960 MHz). Except for the reported one in [4] that has a complicated feeding-network and rotating stacked structures, the proposed antenna has demonstrated a smaller planar size ($200 \times 200\,\mathrm{mm}^2$) compared with all the reference ones in the table. In addition to that, the proposed antenna has also exhibited a slightly larger maximum gain of 8.8 dBic. Nonetheless, the small planar size of this proposed antenna came with a disadvantage of a higher antenna height of 48 mm, as compared with the reference ones.

6. Conclusion

A double-layer stacked patch antenna for universal UHF RFID applications has been successfully proposed. The proposed antenna has been shown to exhibit a desirable 10-dB return loss bandwidth (823–966 MHz), a broad CP bandwidth (837–963 MHz), a good peak gain of 8.8 dBic, and radiation efficiencies of more than 85% across the UHF RFID bands between 840 and 960 MHz. Because of its small planar size, the proposed antenna is a good candidate for universal UHF RFID reader applications.

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