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Design of Miniaturized Quasi-Yagi Antenna for Portable RFID Reader Applications

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Abstract—A method to design a miniaturized two-element quasi-Yagi antenna (QYA) with size and gain requirements is presented for portable ultra high frequency (UHF) radio frequency identification (RFID) reader applications. The antenna consists of a driver dipole and a ground reflector, and these elements are serially connected with a coplanar strip line. The ends of both elements are folded back toward each other to reduce the lateral size of the antenna. A detailed design procedure of the proposed antenna is explained, along with a performance comparison for the input impedance, voltage standing wave ratio (VSWR), broadside gain, front-to-back (F/B) ratio, and total efficiency. A prototype antenna, covering the 860–960 MHz UHF RFID band with a gain $>$ 4 dBi, is fabricated on an FR4 substrate with dimensions limited to 90 mm by 90 mm. The total width of the proposed antenna is reduced by approximately 41% compared to the conventional QYA without miniaturization, and an F/B ratio is improved by 1–8 dB in the band. Experiment results show that the proposed antenna has the desired impedance characteristics with a frequency band of 853–1,098 MHz for a VSWR $<$ 2, and a stable broadside gain of 4.0–5.3 dBi in the UHF RFID band. Moreover, a measured F/B ratio $>$ 13 dB is obtained.

1. INTRODUCTION

Yagi antennas have been widely used to achieve high gain and unidirectional radiation patterns with a very simple structure [1]. A planar quasi-Yagi antenna (QYA) printed on a substrate consists of a strip dipole (driver), a truncated ground plane (reflector), and one or more parasitic strips (directors) [2]. Planar QYAs have been widely used in ultra high frequency (UHF) and microwave applications, such as indoor digital TV and mobile base stations because of their advantageous properties: broad bandwidth, moderate gain, high front-to-back ratio, low cross-polarization level, and ease of fabrication [3, 4].

In recent years, radio frequency identification (RFID) has been gaining lots of attention in the area of automatic identification such as supply chain management (SCM) and inventory control, for companies in the manufacturing and retail sectors as a complementary or replacement technology for bar codes because of its ability to improve efficiency in SCM and inventory management. UHF passive RFID systems have lots of advantages compared to lower frequency band RFID systems such as high frequency (HF) band because of their long read range, high data rate, high read rate, and low cost [5]. For applications involving item-level management, an RFID handheld reader with a personal data assistant plays an important role owing to its advantages in compactness, flexibility, and maneuverability. The most critical requirement for the handheld reader antenna is a compact size with minimum degradation in performance [6].

Various antenna configurations have been used for UHF RFID handheld readers. A meandered printed dipole with a closely-coupled parasitic element backed by a folded ground plane was used to

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achieve 3–4.7 dBi gain in a frequency band of 900–960 MHz with dimensions of 90 mm by 90 mm [7]. A compact three-element Yagi antenna with maximum gain of 6.1 dBi and a voltage standing wave ratio (VSWR) better than 2 in a frequency range of 828–907 MHz was proposed for a handheld UHF RFID reader [8]. In this case, the dimensions were approximately 100 mm by 100 mm. A Koch-shaped log-periodic dipole array antenna with closely coupled parasitic strip elements and a gain of 4–5.7 dBi in a frequency band of 840–960 MHz was introduced [9]. However, the dimensions of the antenna were 107 mm by 124 mm, which is quite large compared to others. Recently, a dual-band antenna consisting of 1-by-2 aperture-coupled patch arrays for UHF and microwave band RFID handheld reader applications was reported [10]. The antenna exhibited an average gain of 3 dBi in the UHF band and its dimensions were 74 mm by 160 mm. However, these antennas are difficult to model because the geometries of the antennas are complex.

In this paper, a miniaturized two-element QYA with an integrated balun is proposed for UHF RFID handheld reader applications. The proposed QYA consists of a driver dipole and a ground reflector connected through a coplanar strip (CPS) line. In order to reduce the lateral size of the antenna, the ends of the two elements are folded back toward each other. The design procedure of the proposed QYA is explained with the performance comparison of three antenna structures (dipole only, conventional two-element QYA, and proposed QYA with folded parts). In addition, the effects of geometrical parameters related to the miniaturization on antenna performance are carefully investigated. The geometrical parameters of the antenna are optimized through a parametric study to cover the 860–960 MHz UHF RFID band with a gain $>$ 4 dBi, and dimensions are limited to 90 mm by 90 mm. The results in this work were obtained using a commercial electromagnetic simulator, CST Microwave Studio (MWS), and were validated by measurements of input VSWR, gain, and radiation patterns tested in an anechoic chamber.

2. ANTENNA GEOMETRY AND DESIGN

The geometry of the proposed two-element QYA is shown in Figure 1. It consists of a strip dipole (**D**) and a ground reflector (**R**), and is printed on an FR4 substrate with a dielectric constant of 4.4 and a thickness of 1.6 mm (loss tangent = 0.025). In order to reduce the large ground size caused by a feed structure with a balun, an integrated balun between the microstrip (MS) line and the CPS line is implemented on the CPS line. The end of the MS line is short-circuited using a shorting pin at the feed point. The ends of the two elements are folded back toward each other to reduce the lateral size of the antenna. The length and width of **D** are l_d and w_d, respectively, whereas those of **R** are l_g and w_g, respectively. The folded length of **D** is l_{bd}, whereas that of **R** is l_{bg}. The distance between **R** and **D** is l_s. The widths of the CPS line and the slot line are denoted as w_{cps} and w_s, respectively. The width of the MS feed line is w_f, and the MS feed is offset from the center at a distance of x_f. The distance between the feed point and **R** is d_f. The length and width of the substrate are L and W, respectively.

Figure 2 shows the three antenna structures to illustrate the design procedure for the proposed antenna, and the corresponding simulated characteristics such as input impedance, VSWR, broadside (the y-axis direction) gain, front-to-back (F/B) ratio, and total efficiency are presented in Figure 3. First, a dipole antenna without the ground reflector is considered, as shown in Figure 2(a). The key design parameters for this case are the dipole length l_d and feed point distance d_f, and these are adjusted to cover the 860–960 MHz UHF RFID band. The selected design parameters are as follows (units in millimeters): $L = 152$, $W = 90$, $l_d = 130$, $w_d = 7.5$, $d_f = 60$, $l_s = 66$, $l_{bd} = l_{bg} = 0$, $l_g = 20$, $w_g = 10$, $w_{cps} = 20$, $w_s = 3.5$, $w_f = 3$, $x_f = 5$, and $h = 1.6$. As can be seen from Figure 3, the frequency band for a VSWR < 2 is 854–968 MHz, and the broadside gain ranges from 0.9 dBi to 1.5 dBi in the UHF RFID band. The input resistance decreases from 100 ohm to 57 ohm, whereas the input reactance increases from -14 ohm to 37 ohm in the UHF RFID band. In addition, the F/B ratio is less than 0.4 dB, and this corresponds to that of the typical broadband half-wavelength dipole antenna. The simulated total efficiency ranges between 78 and 90% in the UHF RFID band.

Next, the ground reflector is added to the dipole, which becomes a two-element QYA, to enhance the directivity and F/B ratio of the antenna, as shown in Figure 2(b). The length and width of the ground reflector are $l_g = 152$ and $w_g = 10$, and other design parameters are the same as those of Figure 2(a). In this case, the frequency band for a VSWR < 2 is 848–970 MHz, and the broadside gain ranges from 4.3 dBi to 6.0 dBi in the UHF RFID band. The input resistance increases from 36 ohm to 87 ohm, whereas the input reactance also increases from −13 ohm to 21 ohm in the UHF RFID band. The F/B ratio ranges from 5.1 dB to 9.6 dB, but it is still less than 10 dB. The simulated total efficiency ranges between 84 and 95% in the UHF RFID band.

Finally, the proposed QYA with the folded parts in both dipole and ground reflector is designed to obtain a broadside gain > 4 dBi in the UHF RFID band with dimensions limited to 90 mm by 90 mm. The lengths of the dipole and ground reflector are fixed at $l_d = l_g = 90$, which are the same as the length of the antenna, and other geometric parameters are optimized through a parametric study. As shown in Figure 3, when the folded parts are added in both dipole and ground reflector, the proposed QYA

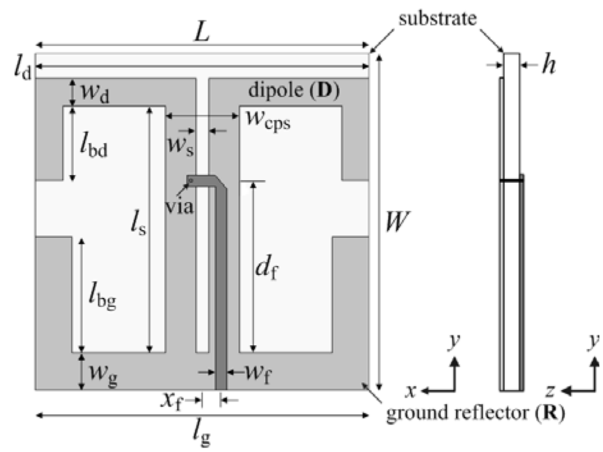

Figure 1. Geometry of proposed QYA with folded parts.

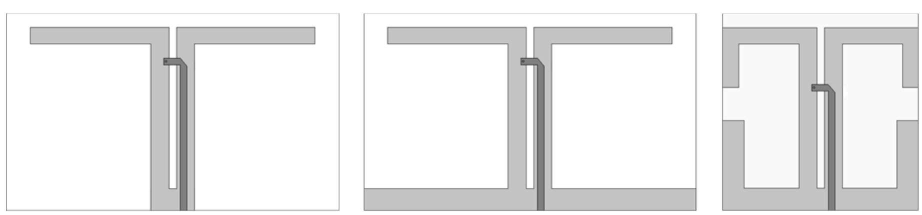

Figure 2. Design procedure for proposed antenna: (a) dipole only, (b) conventional QYA with dipole and reflector, and (c) proposed miniaturized QYA with folded parts in both ground reflector and driver dipole.

Table 1. Optimized design parameters of proposed antenna.

parameter	value (mm)	parameter	value (mm)
L	90	l_s	66
W	90	w_{cps}	20
l_d	90	w_f	3
l_{bd}	20	w_s	3.5
w_d	7.5	x_f	5
l_g	90	d_f	46
l_{bg}	31	h	1.6
w_g	10		

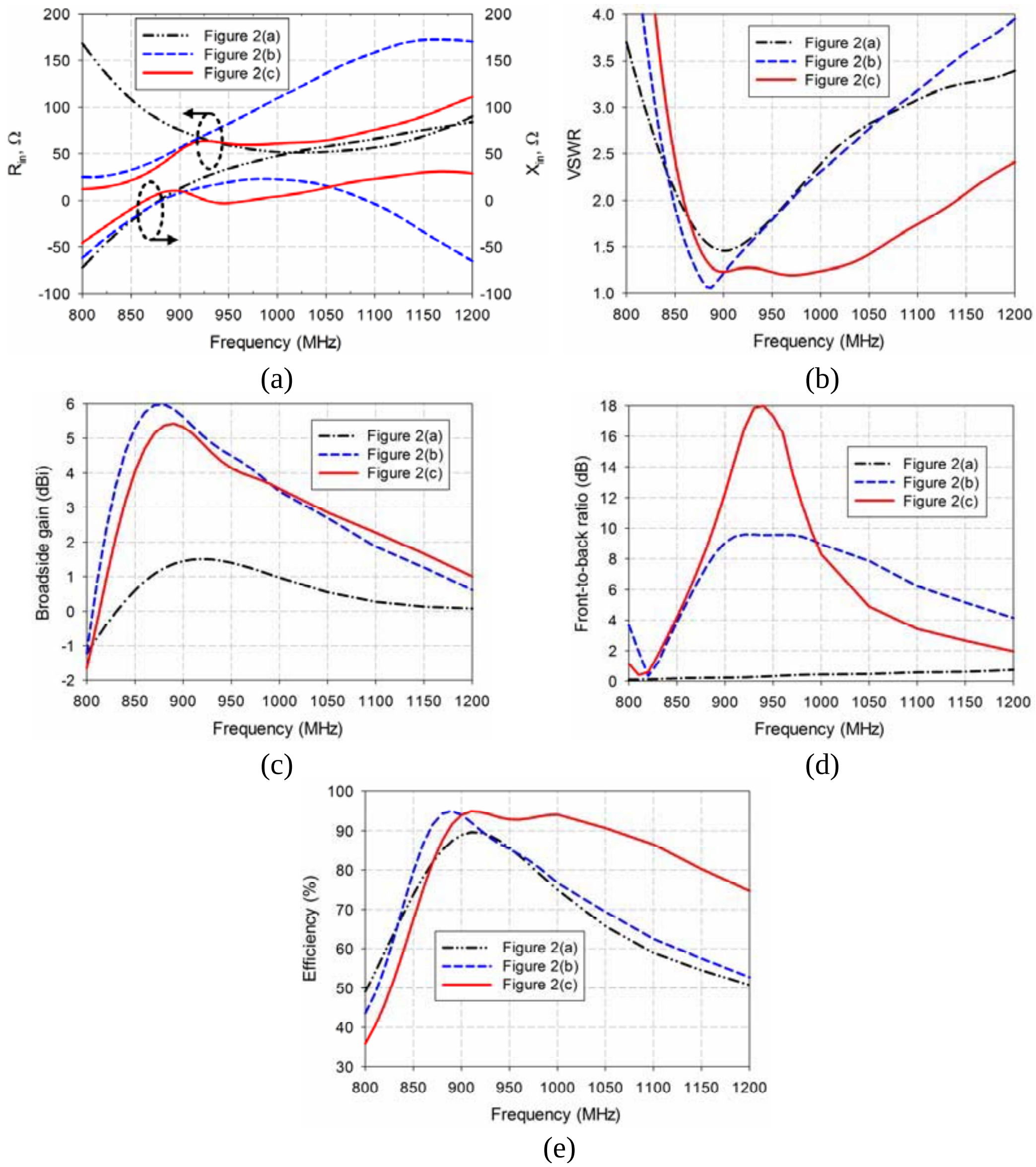

Figure 3. Performance comparison of three antenna structures in Figure 2: (a) input impedance, (b) VSWR, (c) broadside gain, (d) F/B ratio, and (e) total efficiency.

exhibits a very wide frequency band of 859–1,141 MHz, for a VSWR $<$ 2. The broadside gain ranges from 4.0 dBi to 5.4 dBi in the UHF RFID band. The decrease in the broadside gain is only 0.3–0.6 dBi in the UHF band, which might be minimal degradation considering the lateral size reduction of 41%. In addition, the F/B ratio ranges from 5.6 dB to 18.0 dB, and the enhancement in the F/B ratio is 0.5–8.4 dB compared to the conventional QYA in Figure 2(b). In this case, the simulated total efficiency ranges between 75 and 95% in the UHF RFID band.

The crucial geometric parameters affecting the performance of the proposed antenna are the folded length of **D** (l_{bd}), the folded length of **R** (l_{bg}), and the distance between **R** and **D** (l_s). The effects of these parameters on the input VSWR and broadside gain characteristics of the proposed QYA are shown in Figure 4. First, as l_{bd} increases, the frequency bands for impedance and gain move lower, and their bandwidths remain almost the same, as shown in Figure 4(a). However, the maximum gain decreases slightly. Second, the impedance and gain bands move toward a lower frequency as l_{bg} increases, as shown in Figure 4(b). The bandwidth of the frequency band for a VSWR $<$ 2 increases when l_{bg} increases because the lower limit decreases and the upper limit remains almost the same. On the other hand, the frequency bandwidth for a gain > 4 dBi decreases. Third, the lower limit of the impedance frequency band increases, and the upper limit decreases, as l_s increases, as shown in Figure 4(c). Hence, the impedance bandwidth decreases. However, both the lower and upper limits decrease for the frequency band for a gain > 4 dBi, and the bandwidth increases slightly. Maximum gain in the band remains almost constant. From the results of the parametric study, shown in Figure 4, the final optimized design parameters of the proposed QYA related to the miniaturization to achieve a gain > 4 dBi in the UHF RFID band are as follows: $l_{bd} = 20$, $l_{bg} = 31$, and $l_s = 66$. Table 1 summarizes the optimized design parameters to achieve a gain > 4 dBi in the frequency range of 860–960 MHz.

Figure 5 compares the radiation patterns of the three antenna structures in Figure 2 in the E- and H-planes at 910 MHz, and the improvement in the F/B ratio is clearly observed.

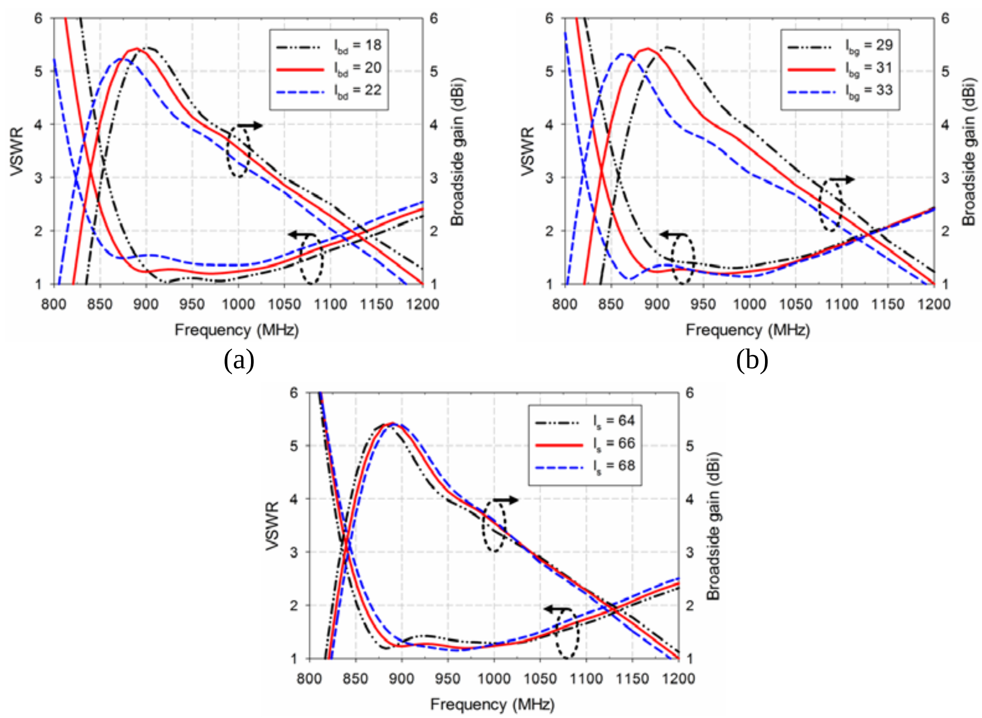

Figure 4. Effects of crucial geometric parameters on input VSWR and broadside gain of proposed antenna: (a) l_{bd}, (b) l_{bg}, and (c) l_s.

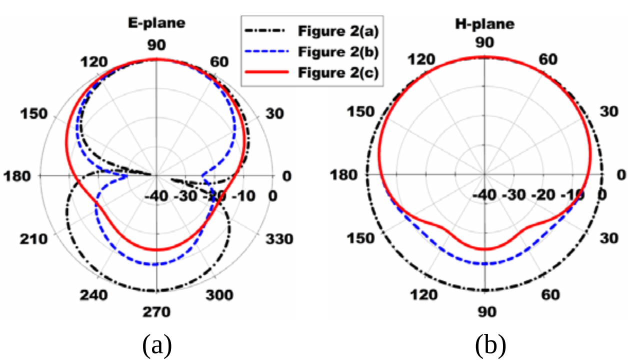

Figure 5. Simulated radiation patterns of three antenna structures in Figure 2 in E- and H-planes at 910 MHz.

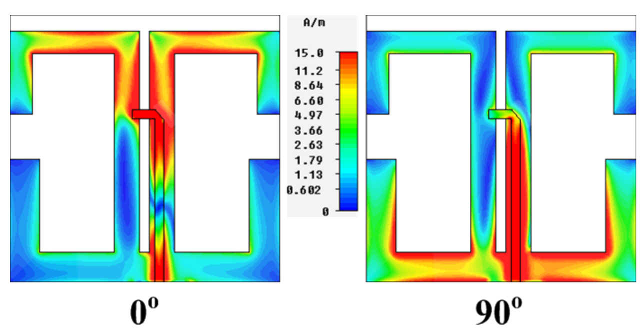

Figure 6. Surface current distribution of proposed antenna at 910 MHz.

The simulated surface current distributions of the proposed antenna at 910 MHz are shown in Figure 6. If we define '0° state' as the state when the dipole element is fully excited, the ground reflector is excited after 90° phase lag, and this state is called '90° state'. This phenomenon clearly shows the operational principle of the two-element QYA.

3. EXPERIMENT RESULTS

A prototype of the proposed QYA is fabricated on an FR4 substrate. Figure 7 shows the photographs of the fabricated antenna.

Figure 8 compares the input VSWR and broadside gain characteristics of the fabricated antenna. An Agilent N5230A network analyzer was used to measure the input VSWR and gain. As shown in Figure 8(a), the simulated frequency band for a VSWR < 2 is 857–1,141 MHz, whereas the measured characteristic is 853–1,098 MHz. The measured results show a slight shift toward a lower frequency and a small decrease in the bandwidth, but the bandwidth is broad enough to cover the UHF RFID band. Simulated broadside gain ranges from 4.0 dBi to 5.4 dBi in the UHF RFID band, whereas it ranges from 4.0 dBi to 5.3 dBi for the measured characteristic, as shown in Figure 8(b).

Table 2 compares the performance of the proposed antenna with those in references [7, 9]. We can see from Table 2 that the impedance bandwidth of the proposed antenna is wider than those in the references. The minimum gain in the 860–960 MHz UHF RFID band is 4.0 dBi, which is higher than the other antennas. In addition, the F/B ratio of the proposed antenna is larger than 13 dB, which is better than other antennas.

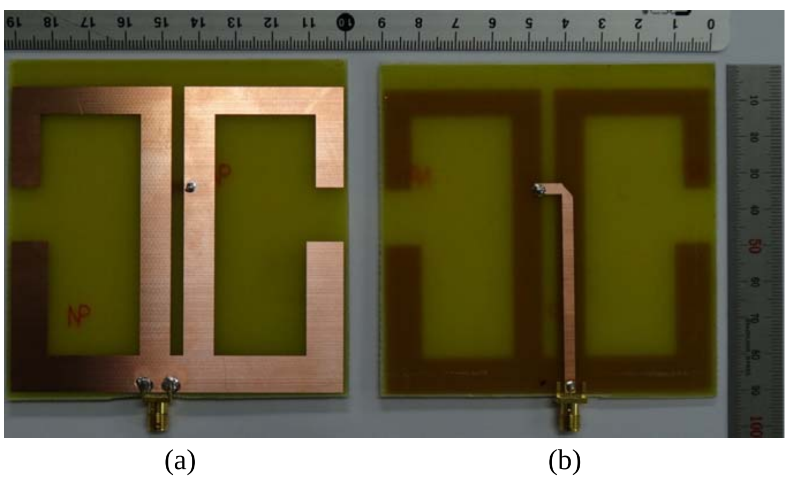

Figure 7. Photographs of fabricated antenna: (a) front view and (b) back view.

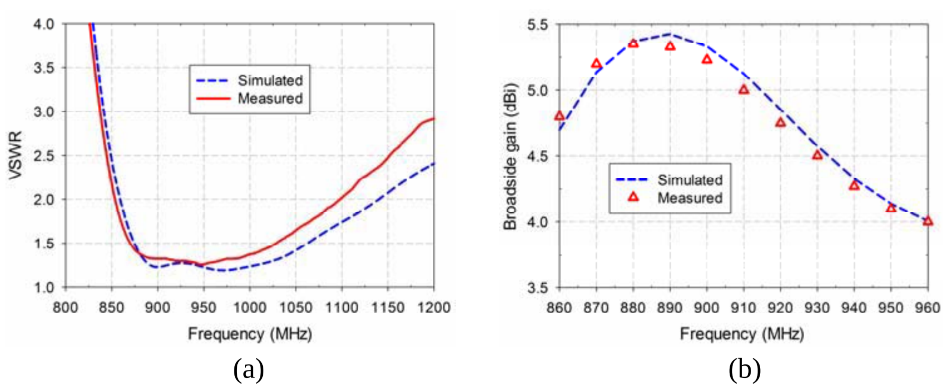

Figure 8. (a) Input VSWR and (b) broadside gain of fabricated antenna.

Table 2. Performance comparison of proposed antenna.

	Size (mm × mm)	VSWR < 2 Bandwidth (MHz)	Gain (dBi)	F/B ratio (dB)
Proposed	90 × 90	853–1,098 (25.1%)	4.0–5.3	15 (860 MHz) 20 (910 MHz) 13 (960 MHz)
[7]	90 × 90	892–990 (10.4%)	2.0–4.7	8.5 (902 MHz) 13 (928 MHz)
[9]	124 × 107	820–982 (18.0%)	3.5–5.7	17 (915 MHz) 12 (953 MHz)

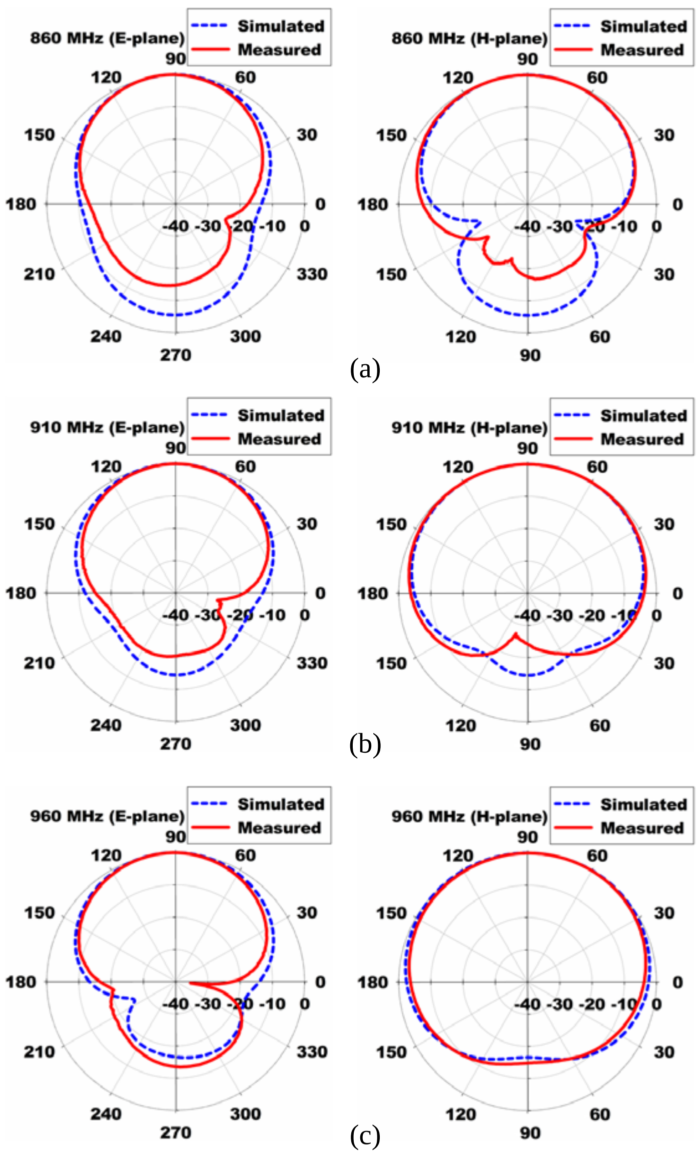

Figure 9. Measured radiation patterns of proposed antenna in E-plane and H-plane at (a) 860 MHz, (b) 910 MHz, and (c) 960 MHz.

Figure 9 compares the radiation patterns of the fabricated antenna in the E-plane (x-y plane) and H-plane (y-z plane) at 860 MHz, 910 MHz, and 960 MHz. The simulated and measured patterns agree well with each other, and the proposed antenna has end-fire directional patterns with a measured front-to-back ratio > 13 dB in the UHF RFID band.

4. CONCLUSION

We have presented a miniaturized two-element QYA consisting of a strip dipole and a ground reflector for portable UHF RFID reader applications. An integrated balun is employed to match the input impedance of the antenna to the 50 Ω feed line, and the ends of both elements are folded back toward each other to reduce the lateral size of the antenna.

A prototype antenna optimized to cover the 860–960 MHz UHF RFID band with a gain > 4 dBi is fabricated on an FR4 substrate with dimensions of 90 mm by 90 mm. The total width of the proposed antenna is reduced by approximately 41% compared to the original antenna without folded parts. The proposed QYA is compact in lateral size because its width (90 mm) corresponds to only $0.26\lambda_0$, where λ_0 is the free space wavelength at the lower frequency limit of 860 MHz. The measured frequency band for a VSWR < 2 is 853–1,098 MHz, and the measured gain ranges from 4.0 dBi to 5.3 dBi in the UHF RFID band. The measured front-to-back ratio is larger than 13 dB.

The proposed antenna is expected to be suitable for UHF RFID handheld readers.

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