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Single-Feed Composite Cavity-Backed Four-Arm Curl Antenna

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Abstract

A single-feed composite cavity-backed four-arm curl antenna is presented for use in global positioning systems (GPS). Its primary radiating element is fed by a vacant-quarter printed ring, which helps the antenna directly match to a 50-Ω coaxial line and produce a good circular polarization (CP). The cavity-backed reflector is employed to improve the CP radiation characteristics in terms of 3-dB axial ratio (AR) beamwidth and minimum AR value. The optimized design with an overall size of 90 × 90 × 25 mm^3 (0.4725 λ_o × 0.4725λ_o × 0.13 λ_o at 1,575 MHz) results in a $|S_{11}|$ < −10 dB bandwidth of 8.66% (1,514–1,651 MHz) and a 3-dB AR bandwidth of 2.23% (1,555–1,590 MHz). The antenna radiates a widebeam right-hand circular polarization and operates with a measured radiation efficiency greater than 90% within its impedance matching bandwidth.

Key Words: Curl Antenna, Circular Polarization, Global Positioning System, Vacant-Quarter Printed Ring.

I. Introduction

Archimedean spiral antennas belong to a class of traveling-wave wideband antennas that radiate a circularly polarized (CP) wave. The primary radiating elements of these antennas can be single-arm [1], two-arm [2–4], or four-arm [5] configurations with a large number of turns. Four-arm spiral antennas are considerably superior in performance to their single- and two-arm counterparts [6]. However, the four-arm spiral antenna generally requires a feed that has four output lines with equal amplitudes and a sequentially rotated phase [7]. This feeding structure contains a 1-to-4 power combiner/splitter that is generally complex, bulky, and expensive. In addition, the spiral antennas need a balun in the feed for matching to a 50-Ω coaxial cable since the input impedance is usually high (approximately 188-Ω for a self-complementary spiral antenna in free space) [8, 9]. As a result, the design of four-arm spiral antennas faces the main challenge of implementing a simpler feeding structure.

On the other hand, short Archimedean spiral antennas [10–13], which are also referred to as curl antennas, behave as resonant types of antennas. These antennas are mechanically simple and produce CP radiation from a single feed point without the need for an external circuit; i.e., the antennas can be directly matched to a 50-Ω coaxial line. The selected curl antenna is placed approximately a quarter wavelength of the considered medium above a large perfect electric conductor surface, consequently, it can provide a good impedance matching and a good CP radiation over a bandwidth of approximately 10%. The radiation patterns of these antennas, however, are not very symmetric due to the single-arm configuration.

This paper introduces a single-feed four-arm curl antenna backed by a cavity reflector for global positioning systems (GPS) applications. A pair of vacant-quarter printed rings is employed in the feed of the radiator for direct matching to a 50-Ω coaxial

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line and to produce a CP radiation. The incorporation of the cavity-backed reflector [14, 15] is a simple technique to improve the CP radiation characteristics in terms of 3-dB AR bandwidth and high-front-to-back ratio. The resulting antenna is characterized first with the ANSYS-Ansoft High Frequency Structure Simulator (HFSS) [16] and its simulated performance is then verified by measurements. In comparison with the previous wide-beam GPS antennas [14, 15], the proposed antenna yields the same CP radiation performance with smaller antenna dimensions.

II. Antenna Geometry

Fig. 1 shows the geometry of the proposed antenna composed of a four-arm curl radiator, a coaxial line, and a reflector. The curl radiator, which is a four-arm Archimedean spiral antenna with a small number of turns, was built on both sides of a circular Rogers RO4003 substrate with a radius of R_{sub}, a relative permittivity of 3.38, a loss tangent of 0.0027, and a thickness of $h_s = 0.508$ mm (20 mils). Two blue arms were placed on the bottom side of the substrate, whereas two other arms (red color) were on the top side of the substrate. The curl arm was characterized by an Archimedean spiral drawing function of the HFSS software [16], which is defined by a center position of (0, 0, 0), a direction vector (0, 0, 1), a starting point of R_0, a radius change of R_c, a number of turns of n, and a strip width of W_s. The radiator is fed by a vacant-quarter printed ring, which helps the antenna directly match to a 50-Ω coaxial line with a broad impedance matching bandwidth and provide the CP radiation. The reflector is a rectangular box with base dimensions of 90 × 90 mm^2 and a height of H_c. The optimized antenna design parameters were chosen for the compact size, the minimum AR at 1,575 MHz, and the wide CP radiation beamwidth as follows: $R_{sub} = 35$ mm, $R_c = 25$ mm, $R_0 = 8$ mm, $R_r = 5$ mm, $W_r = 1$ mm, $w_b = 5$ mm, $W_s = 3$ mm, $h_s = 0.508$ mm, $H = 25$ mm, $H_c = 25$ mm, and $n = 1$.

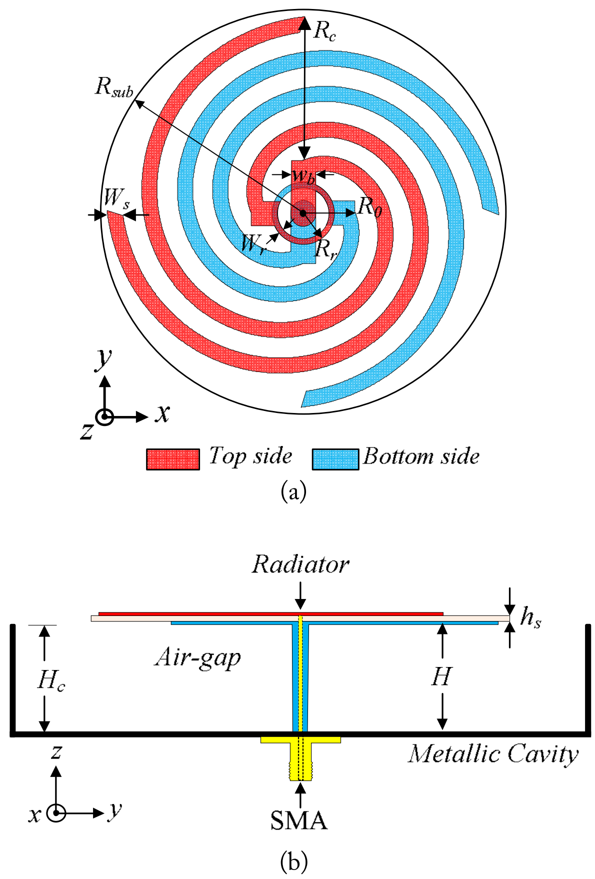


Fig. 1. Geometry of the proposed antenna. (a) Radiator and (b) cross-section view with the cavity-backed reflector.

III. Antenna Design

1. Condition for CP Radiation

The curl antenna normally behaves as a resonant antenna and its input impedance depends on the number of turns, the spacing between turns, and the width of arm as well as the dielectric substrate (permittivity and thickness). Accordingly, the input impedance of the four-arm curl antenna can be predictively determined to match directly to a 50-Ω coaxial line. An ideal four-arm curl antenna, as shown in Fig. 2, was chosen for the initial design of the radiator and characterized by the HFSS software. The arms were placed on both sides of a circular Roger RO4003 substrate; the blue arms (#2 and #4) were on the bottom side of the substrate and the red arms (#1 and #3) were on the top side of the substrate. Referring to Fig. 1(a), the arm was formed by a center position of (0, 0, 0), a direction vector (0, 0, 1), $R_0 = 9$ mm, $R_c = 25$ mm, $n = 1$, and $W_s = 3$ mm. The antenna was simulated by assuming two excitation sources (port-1 for the red arms and port-2 for the blue arms) and their input impedances (Z_{11} or Z_{22}) were calculated and given in Fig. 3. Since the Z_{11} value is completely the same as Z_{22} and expresses the input impedance of the ideal four-arm curl antenna, Fig. 3 only shows the real and imaginary parts of Z_{11}. With the

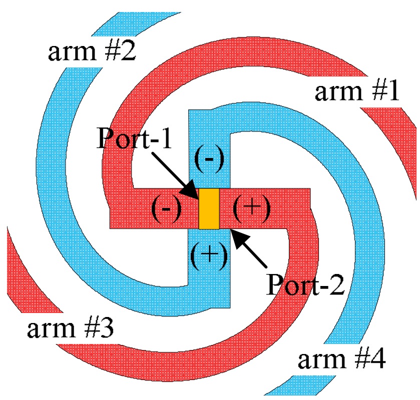


Fig. 2. High frequency structure simulator simulation modeling for an ideal four-arm curl antenna.

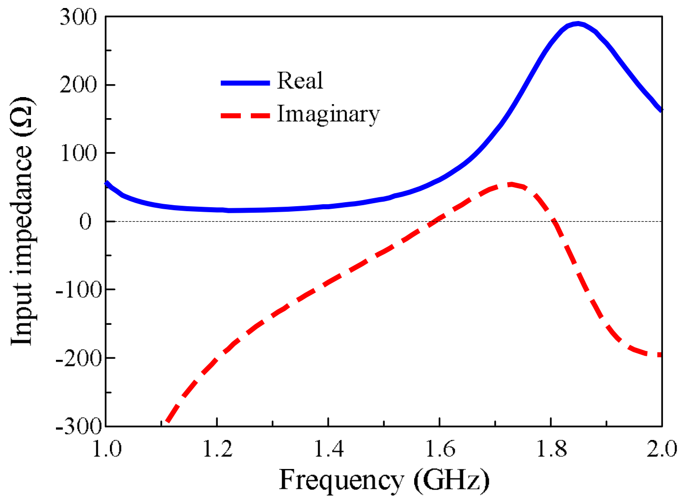


Fig. 3. Simulated input impedance (Z_{11} or Z_{22}) of the ideal four-arm curl antenna.

chosen parameters, the antenna yielded two resonances in the frequency range of interest (i.e., the resonance was defined as the frequency at which the imaginary value equals to 0). The first one was 1,580 MHz with a real value of approximately 50-Ω while the second one was 1,790 MHz with a real value of approximately 290-Ω. This result indicates that the antenna can be matched well to a 50-Ω coaxial line without the need for an external circuit at its first resonance. In order to have a CP wave, the two excitation sources must have equal amplitudes and a 90° phase difference; consequently, the antenna requires a 1-to-2 power combiner/splitter and a 1/4 wave phasing line in the feeding structure. This approach could complicate the antenna design and fabrication.

On the other hand, a single feed crossed dipole antenna [17] could generate CP radiation if the lengths of the dipoles are chosen such that the real parts of their input admittances are equal and the phase angles of their input admittances differ by 90°. At the desired frequency, the longer one has an inductive reactance, while the shorter one has a capacitive reactance. According to these conditions, the four-arm curl antenna could radiate a CP wave with a single feed. The required power and phase relationships can be obtained by proper choice of the number of turns for each arm of the antenna. This is observed in Fig. 4, which shows the input admittance of the ideal four-arm curl antenna (Fig. 2) at 1,575 MHz for different numbers of turns (n). The condition for CP radiation can be determined from an accurate plot of input admittance by a graphical solution, as shown in Fig. 4; i.e., the number of turns for #1 and #3 arms is approximately 0.93, whereas the number of turns for #2 and #4 arms is approximately 1.01.

2. Four-Arm Curl Antenna Fed by Double Vacant-Quarter Printed Rings

The condition for CP radiation mentioned in the subsection

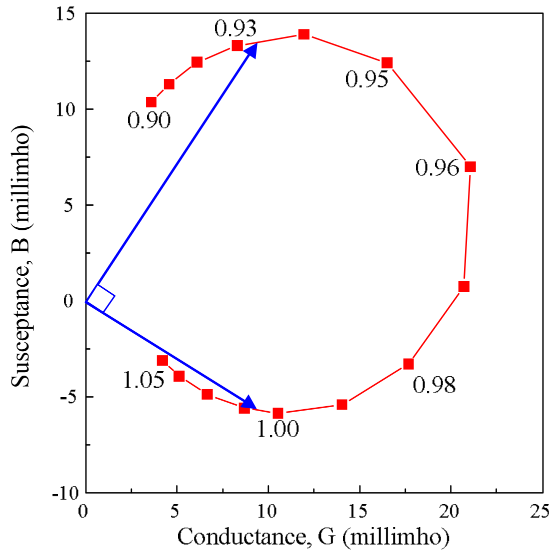


Fig. 4. Input admittance at Port 1 (or Port 2) of the ideal four-arm curl antenna at 1,575 MHz for different numbers of turns (n).

A can be obtained in two equal length dipoles with a single feed by using a pair of vacant-quarter printed rings [14, 15]. Accordingly, this approach is applied to the four-arm curl antenna with the same number of turns for all arms in order to produce the CP radiation and direct matching to a single 50-Ω coaxial line. The presence of the printed rings slightly changed the antenna geometry shown in Fig. 1(a) when compared with the ideal design (Fig. 2). The antenna was optimized for a minimum AR value at the GPS L1 frequency. Referring to Fig. 1(a), the antenna design parameters were as follows: R_{sub} = 25 mm, R_c = 25 mm, R_0 = 9 mm, R_r = 5.4 mm, W_r = 1 mm, w_b = 5 mm, W_s = 3 mm, and h_s = 0.508 mm.

The role of the printed ring was demonstrated by investigating the performances of the antenna with different values of its design parameters (R_r and W_r), as shown in Figs. 5 and 6. As R_r was increased, the resonances slightly changed (Fig. 4(a)), whereas the CP frequency increased (Fig. 4(b)). When W_r was varied from 0.8 mm to 1.2 mm, the impedance matching significantly degraded (Fig. 5(a)), whereas the CP frequency hardly changed (Fig. 5(b)). These results indicate that R_r mainly affects the CP frequency whereas W_r mainly affects the impedance matching.

The simulated performances of the four-arm curl antenna in free space are shown in Fig. 7. The antenna yielded an impedance matching bandwidth of 12.9% (1,520–1,730 MHz) for $|S_{11}| < -10$ dB and a 3-dB AR bandwidth of 3.81% (1,545–1,605 MHz) with the CP center frequency of 1,575 MHz (AR = 0.4) (Fig. 7(a)). At the CP center frequency, the antenna radiated a bidirectional electromagnetic wave with a gain of 3.27 dBic, as shown in Fig. 7(b); the front side was right-hand CP (RHCP), whereas the back side was left-hand CP (LHCP).

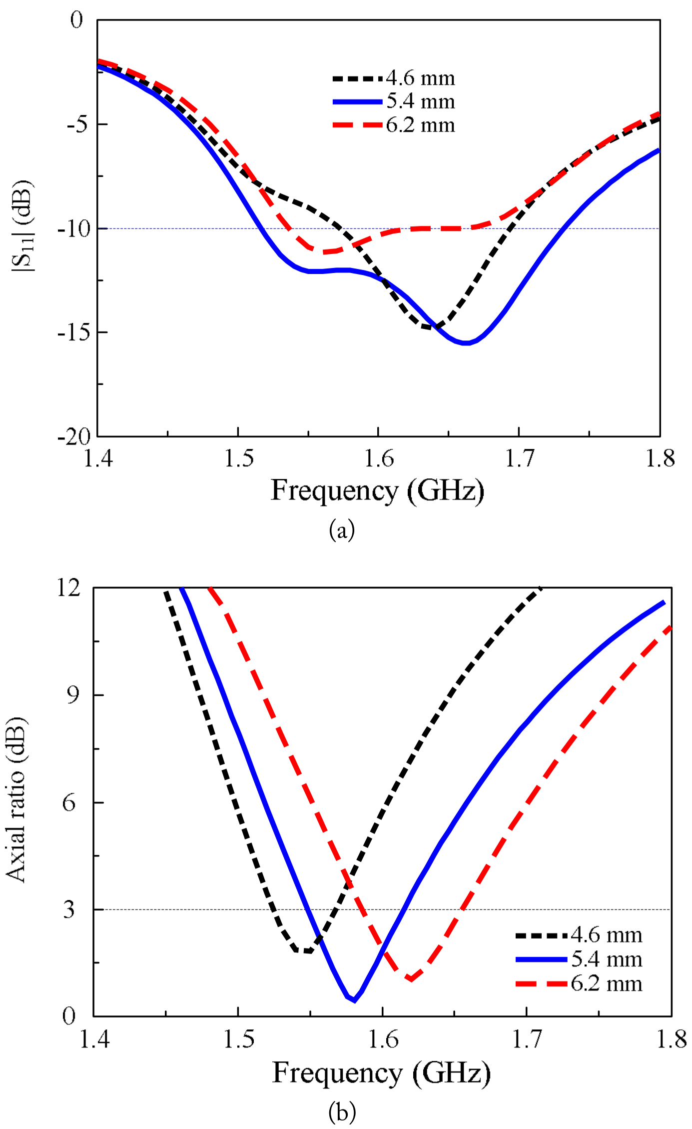


Fig. 5. Simulated (a) $|S_{11}|$ and (b) axial ratio values of the curl antenna in free space for different R_r.

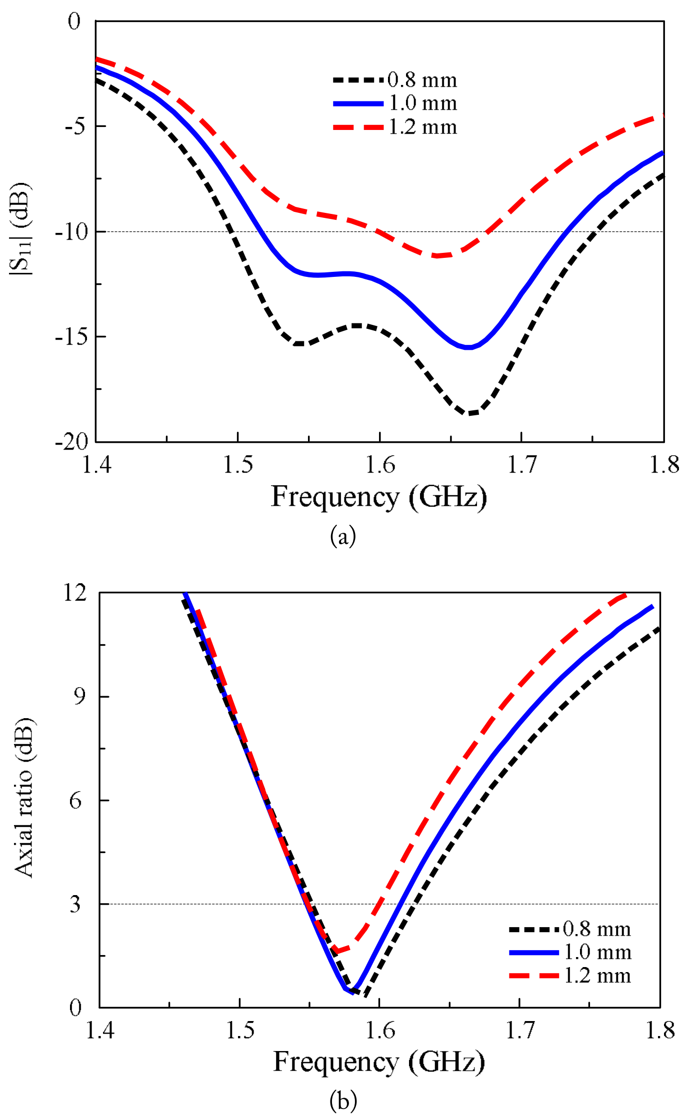


Fig. 6. Simulated (a) $|S_{11}|$ and (b) axial ratio values of the curl antenna in free space for different W_r.

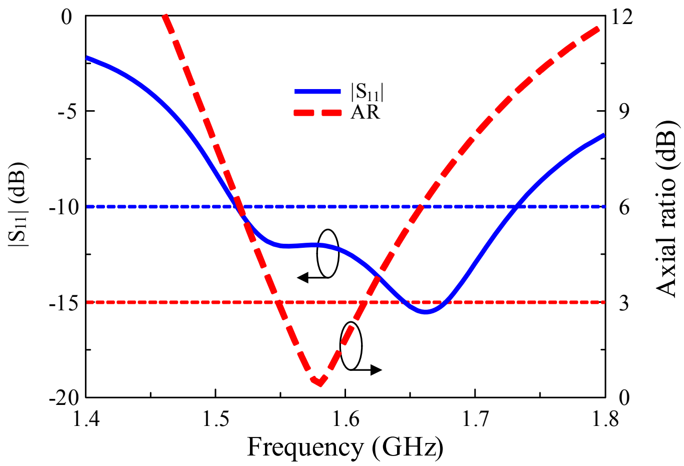
Note that the RHCP and LHCP results are interchangeable simply by reversing the printed ring.

3. Four-Arm Curl Antenna Incorporating with the Cavity-Backed Reflector

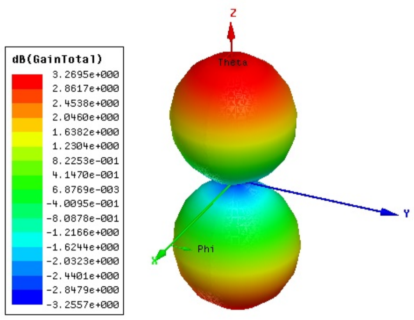
The radiation characteristics were improved and a wide beamwidth and a high front-to-back ratio were obtained by introducing a cavity as a reflector in the four-arm antenna. Both square and circular reflectors were used in the optimization process for the curl antenna. However, the square one, as shown in Fig. 1(b), was chosen for the final design based on a compromise between a small antenna footprint and good CP radiation. The proposed design with the cavity-backed reflector was confirmed to improve the radiation characteristics by examining the antenna performances at different heights (H_c) of the cavity. The corresponding antenna characteristics are summarized in Table 1. A better understanding of the effect of the cavity height on the radiation pattern was obtained by comparing the 3-dB AR beamwidth at the CP center frequency for the different H_c values. The proposed antenna exhibited the maximum 3-dB AR beamwidth at the CP center frequency. As shown in Table 1, an increase in the cavity height (H_c) accompanied a decrease in the operating frequency band of the antenna and a significant widening of the 3-dB AR beamwidth. These results indicated that the cavity-backed reflector facilitates the production of wide-beam radiation.

IV. Measured and Simulated Results

The composite cavity-backed four-arm curl antenna was fabricated and measured. The curl radiator was built on both sides of a circular Rogers RO4003 substrate with a copper



(a)



(b)

Fig. 7. Simulated (a) $|S_{11}|$ and axial ratio values of the four-arm curl antenna fed by double vacant-quarter printed ring in free space and (b) its 1,575-MHz radiation pattern.

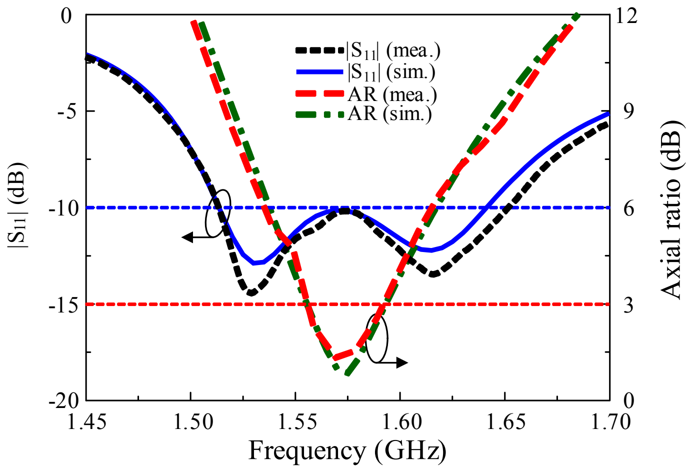
Table 1. Characteristics of the four-arm curl GPS antenna for different heights of the cavity

H_c (mm)	$\|S_{11}\| < -10$ dB bandwidth (MHz)	3-dB AR bandwidth (MHz)	CP center frequency (MHz)	3-dB AR beamwidth at the CP center frequency	
				x-z plane	*y-z* plane
5	1,540–1,695	1,605–1,630	1,615	62°	123°
15	1,525–1,665	1,575–1,610	1,595	101°	134°
25	1,515–1,640	1,555–1,590	1,575	136°	160°

GPS=global positioning system, AR=axial ratio, CP=circular polarization.

thickness of 20 μm via standard etching technology. The cavity-backed reflector was constructed using five copper plates (one 90 × 90 mm² and four 25 × 90 mm²) having a thickness of 0.2 mm. A sample of the proposed antenna (Fig. 8(a)) was used for the measurements; an Agilent N5230A network analyzer and a 3.5-mm coaxial calibration standard GCS35M were used for the input impedance measurement of the antenna. Another Agilent E8362B network analyzer and two identical standard horn antennas were used for the radiation pattern measurements, which were conducted in a full anechoic chamber with the dimensions of 15.2 m (*W*) × 7.9 m (*L*) × 7.9 m (*H*) at RFID/USN Center, Incheon, Korea.

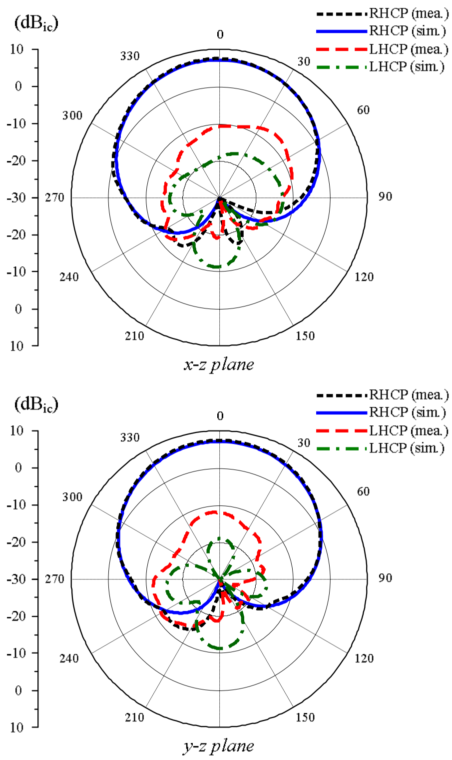
(a)



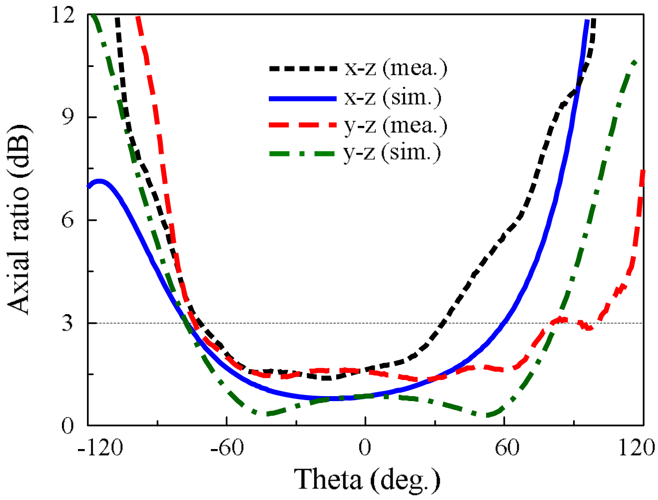
(b)

Fig. 8. (a) Top-view of fabricated sample and (b) simulated and measured $|S_{11}|$ and axial ratio values of the composite cavity-backed four-arm curl GPS antenna.

Fig. 8(b) shows the measured and simulated reflection coefficients for the proposed antenna. The measured bandwidth was 8.66% (1,514–1,651 MHz) for $|S_{11}|$ <–10 dB, which agreed well with the simulated bandwidth of 7.92% (1,515–1,640 MHz). The simulated and measured AR of the proposed antenna are also shown in Fig. 6(b), and showed good agreement. The measured 3-dB AR bandwidth was 2.23% (1,555–1,590 MHz) with the CP center frequency of 1570 MHz (AR of 1.66 dB), while the simulated 3-dB AR bandwidth was 2.54 % (1,555–1,595 MHz) with the CP center frequency of 1,575 MHz (AR of 0.5 dB).



(a)



(b)

Fig. 9. (a) Radiation pattern and (b) axial ratio as function of the theta angle at 1,575 MHz. RHCP=right hand circular polarization, LHCP=left hand circular polarization.

Fig. 9(a) shows the 1,575 MHz radiation pattern of the antenna with RHCP, symmetrical profile, and wide beamwidth in both *x-z* and *y-z* planes. The measurements yielded a gain of 7.4 dBic, a front-to-back ratio of 26 dB, and half-power beamwidth (HPBW) of 100° and 99° in the *x-z* and *y-z* planes, respectively. Fig. 9(b) shows the simulated and measured AR of the antenna versus theta angle at 1,575 MHz and shows a wide 3 dB AR beamwidth; the measured beamwidth for AR<3 dB was 125° and 155° in the *x-z* and *y-z* planes, respectively. The simulated beamwidth for AR<3 dB was 136° and 160° in the x-z and y-z planes, respectively. The measured AR values are not very symmetric in the principal planes. This could be attributed to slight misalignment of the fabricated sample. Additionally, the measured antenna efficiency was greater than 90%, which agreed rather closely with the simulated efficiency of >90% within the operating bandwidth.

V. CONCLUSION

A single-feed composite cavity-backed four-arm curl antenna has been introduced. The antenna with overall GPS L1 frequency size of 0.4725 $\lambda_o \times$ 0.4725 $\lambda_o \times$ 0.13 λ_o resulted in a $|S_{11}|$<−10 dB bandwidth of 8.66% (1,514–1,651 MHz) and a 3-dB AR bandwidth of 2.23% (1,555–1,590 MHz). Furthermore, the antenna radiates wide-beam RHCP (greater than 140°) and operates with a measured radiation efficiency greater than 90% within its impedance matching bandwidth. This antenna has many advantages and can be widely applied to GPS applications and other satellite communications. It can be easily scaled for other wireless communication systems, such as RFID, WLAN, and WiMAX.

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