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Wide-Beam Circularly Polarized Crossed Scythe-Shaped Dipoles for Global Navigation Satellite Systems

Son Xuat Ta[1] · Jea Jin Han[1,2] · Ikmo Park[1,*] · Richard W. Ziolkowski[3]

Abstract

This paper describes composite cavity-backed crossed scythe-shaped dipoles with wide-beam circularly polarized (CP) radiation for use in Global Navigation Satellite Systems. Each branch of the dipole arm contains a meander line, with the end shaped like a scythe to achieve a significant reduction in the size of the radiator. For dual-band operation, each dipole arm is divided into two branches of different lengths. The dipoles are crossed through a 90° phase delay line of a vacant-quarter printed ring to achieve CP radiation. The crossed dipoles are incorporated with a cavity-backed reflector to make the CP radiation unidirectional and to improve the CP radiation beamwidth. The proposed antennas have broad impedance matching and 3-dB axial ratio bandwidths, as well as right-hand CP radiation with a wide-beamwidth and high front-to-back ratio.

Key Words: Cavity-Backed Reflector, Circular Polarization, Meander Line, Phase Delay Line, Scythe Shape.

Ⅰ. Introduction

Global navigation satellite systems (GNSSs), including global positioning system (GPS), GLObal NAvigation Satellite System (GLONASS), Galileo, and Compass, will be fully deployed and operational in a few years [1]. An antenna for a GNSS receiver requires broadband characteristics, such as impedance matching and 3-dB axial ratio (AR) bandwidths, right-hand circularly polarized (RHCP) radiation, a wide CP radiation beamwidth (> 100°) facing the sky, and a high front-to-back ratio. The use of a variety of single- and dual-band CP antennas in the GNSS frequency bands has been reported: e.g., crossed dipole [2－6], microstrip patch [7－10], slotted [11－13], near-field resonant parasitic [14, 15], and stacked patch [16, 17] antennas. However, most of these antennas have insufficient 3-dB AR beamwidth to meet the requirements of GNSS applications, owing to the lack of techniques to broaden the CP radiation beamwidth. Recently, several techniques have been introduced to broaden the CP radiation beamwidth of microstrip patch antenna. These have included a pyramidal ground structure with a partially enclosed flat conducting wall [18], auxiliary radiator [19], applying higher order modes [20], loading gaps and stubs on the patch [21], and microstrip-monopole combination [22]. Most of these techniques are effective only for single-band antennas. The technique for extending the substrate beyond the ground plane was introduced for dual-frequency patch antennas to realize a wide CP radiation beamwidth [23], but its 3-dB AR bandwidths are relatively narrow.

This paper introduces composite cavity-backed crossed scythe-shaped dipoles as a simple method to broaden the CP radiation beamwidth for single- and dual-band operations. A vacant-quarter printed ring acts as a 90° phase

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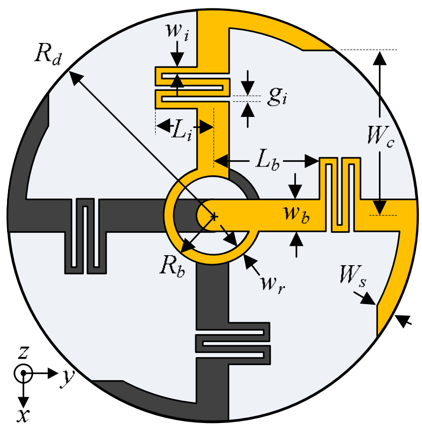
[1]Department of Electrical and Computer Engineering, Ajou University, Suwon, Korea.
[2]Danam Systems, Anyang, Korea.
[3]Department of Electrical and Computer Engineering, University of Arizona, Tucson, AZ, USA.
[*]Corresponding Author: Ikmo Park (e-mail: ipark@ajou.ac.kr)

delay line of the primary radiating element to generate the CP radiation [24]. The crossed scythe-shaped dipole [25] is first characterized in free space and is then incorporated with a cavity-backed reflector. Additional resonances are generated by dividing the dipole arm into two branches with different lengths. Both the single- and dual-band antennas yielded excellent performance in terms of broad bandwidth, wide beamwidth radiation, and high radiation efficiency. Compared to the composite cavity-backed arrowhead-shaped dipoles [26−28], the presented antennas have a wider impedance matching bandwidth, a wider 3-dB AR bandwidth, and a wider CP radiation beamwidth.

Ⅱ. Design of Crossed Scythe-Shaped Dipole in Free Space

Fig. 1 shows the geometry of the crossed dipole without the reflector. Each dipole arm contains a meander line, with the end shaped like a scythe. The scythe-shaped dipoles working at 1.58 GHz were first designed in free space and then crossed through a vacant-quarter printed ring to achieve CP radiation. The antenna was printed on a circular RT/Duroid 5880 substrate with a radius of 25 mm, a relative permittivity of 2.2, a loss tangent of 0.0009, and a thickness of 0.508 mm (20 mils). The antenna was fed with a 50 Ω coaxial line. The outer conductor of the coaxial line was connected to the dipole arms on the bottom side of the substrate. The inner conductor of the coaxial line was extended through the substrate and connected to the dipole arms on the top side. The antenna was optimized via ANSYS high-frequency structure simulator (HFSS) software to have a broad impedance matching bandwidth and a CP center frequency at 1.58 GHz, where the CP center frequency was defined as the frequency at which the minimum AR occurs. The optimized antenna design parameters were: R_d = 25 mm, W_b = 4 mm, R_b = 6 mm, W_r = 1.2 mm, W_c = 20 mm, w_i = 0.8 mm, g_i = 0.6 mm, L_i = 8 mm, w_s = 2 mm, and h = 0.508 mm. Fig. 2(a) shows the simulated reflection coefficient and AR values versus the frequency of the crossed dipole antenna. The impedance bandwidth ranged from 1.495 to 1.800 GHz, and the CP center frequency was 1.58 GHz, at which the AR was 3.2 dB. Additionally, the antenna without the reflector radiated a quasi-bidirectional wave with a gain of 1.87 dBi at the CP center frequency, as shown in Fig. 2(b).



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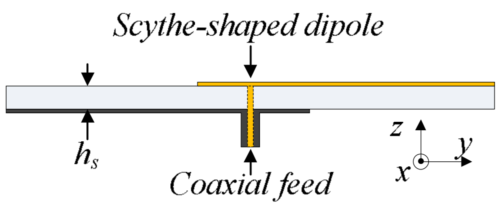

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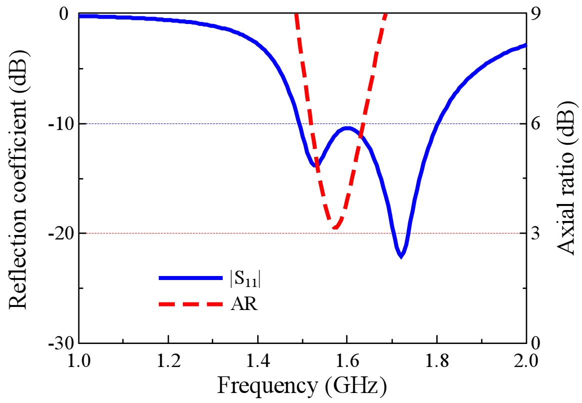
Fig. 1. Geometry of the crossed scythe-shaped dipole antenna in free space. (a) Top view and (b) side view.



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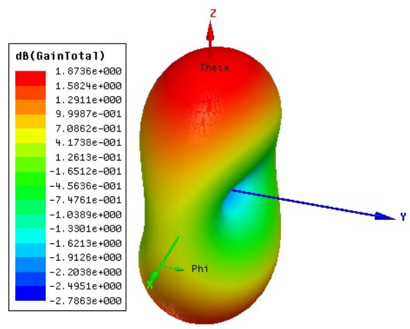

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Fig. 2. (a) Simulated reflection coefficient and axial ratio (AR) of the crossed scythe-shaped dipole in free space and its (b) 3-dimensional radiation pattern at 1.58 GHz.

Ⅲ. Composite Cavity-Backed Crossed Scythe-Shaped Dipole

A unidirectional radiation pattern was achieved and the CP radiation was improved by incorporating a cavity-backed reflector into the crossed scythe-shaped dipoles. A side view of the geometry of the antenna is given in Fig. 3. The reflector is a rectangular box with base dimensions

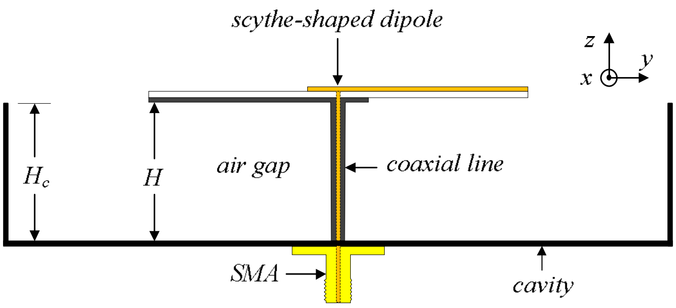


Fig. 3. Side view of the composite cavity-backed crossed scythe-shaped dipole geometry.

of 120 mm × 120 mm and a height of H_c = 40 mm. The crossed dipoles were suspended at the center of the cavity at a height of H = 40 mm from the bottom of the reflector. The coaxial line was passed through the cavity to feed the radiator. The presence of the cavity-backed reflector and the need to keep the CP center frequency at 1.58 GHz meant that the optimized design parameters of the crossed scythe-shaped dipoles were slightly different from those in free space. They were: R_d = 25 mm, W_b = 4 mm, R_b = 6 mm, W_r = 1.2 mm, W_c = 20 mm, w_i = 0.8 mm, g_i = 0.6 mm, L_i = 7 mm, w_s = 2 mm, H_c = 40 mm, and H = 40 mm.

Research has shown that the radiation of a cavity-backed antenna is determined more directly by the electric field distribution in the aperture than by the radiator current [4]. Accordingly, the electric field distribution in the aperture at 1.58 GHz was examined and is illustrated in Fig. 4 for phase angles of 0°, 45°, 90°, and 135°, in order to understand the CP behavior of the proposed cavity-backed antenna. A right-hand rotated electric field is apparently concentrated within the cavity aperture, and a strong electric field is present near the scythe-shaped dipole arms. This indicates that the radiation of the composite cavity-backed crossed scythe-shaped dipole antenna is RHCP.

The characteristics of the antenna at different heights (H_c) with respect to the cavity-backed reflector were studied, and the results are summarized in Table 1. The proposed antenna exhibited the maximum 3-dB AR beamwidth at the CP center frequency. An increase in H_c did not appreciably the impedance bandwidth for a −10 dB

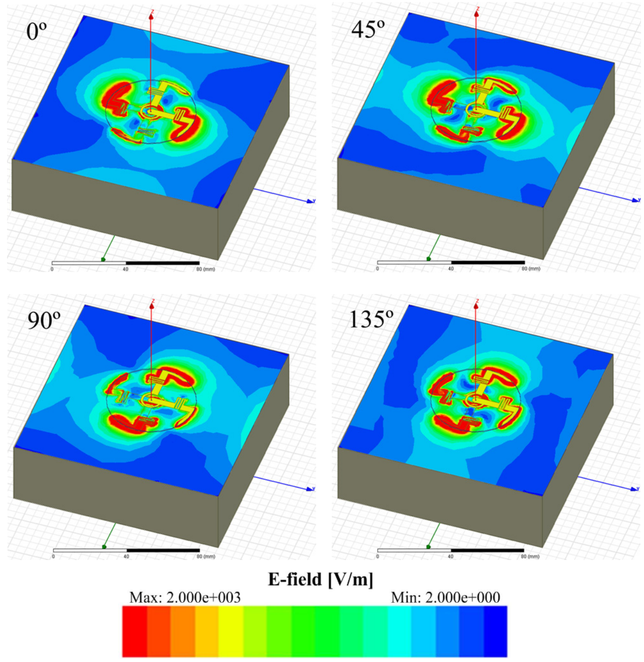


Fig. 4. Simulated electric field distribution in the cavity aperture at 1.58 GHz.

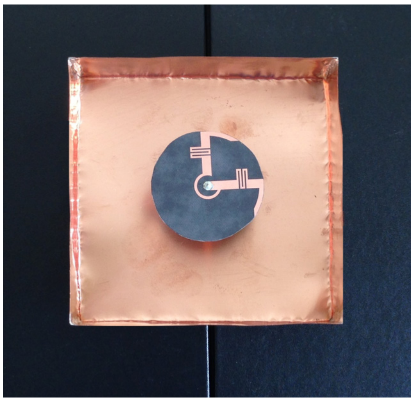
reflection coefficient, but the CP radiation characteristics significantly improved. The CP center frequency decreased, the 3-dB AR bandwidth was enhanced, and the CP radiation beamwidth widened, as shown in Table 1. In addition, HFSS simulations showed that the antenna with H_c < 18 mm yielded an AR > 3 dB and that H_c = 40 mm produced a 3-dB AR beamwidth > 190° in both the x−z and y−z planes. These results indicate that the CP radiation of the scythe-shaped dipole is significantly improved by the use of the cavity-backed reflector.

The proposed composite cavity-backed crossed scythe-shaped dipole antenna was fabricated and measured. The primary radiating elements were built on both sides of the RT/Duroid 5880 substrate with a copper thickness of 17 μm. The cavity-backed reflector was constructed from 5 copper plates (one 120 mm × 120 mm and four 120 mm × 40 mm) with a thickness of 0.2 mm. An Agilent N5230A network analyzer and a 3.5-mm coaxial calibration

Table 1. Performance characteristics of the crossed scythe-shaped dipole antenna for different cavity heights

H_c (mm)	Impedance bandwidth (GHz)	3-dB AR bandwidth (GHz)	CP center frequency (GHz)	3-dB AR beamwidth at the CP center frequency (°)	
				x−z plane	y−z plane
0	1.495−1.830	0	1.605	0	0
10	1.490−1.840	0	1.605	0	0
20	1.485−1.830	1.585−1.605	1.595	36	146
30	1.480−1.835	1.555−1.625	1.585	110	174
40	1.480−1.890	1.530−1.615	1.570	198	209

AR = axial ratio, CP = circularly polarized.



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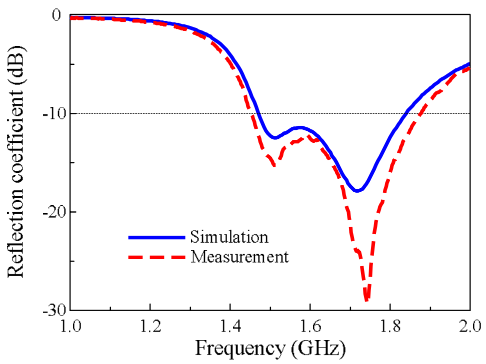

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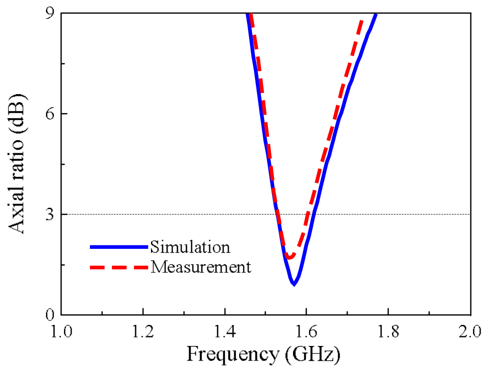
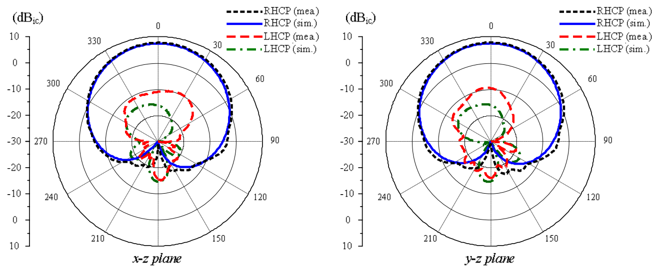


(c)

Fig. 5. (a) Top-view of a fabricated sample of the composite cavity-backed scythe-shaped dipole antenna. Comparison of the simulated and measured (b) reflection coefficient and (c) axial ratio values.



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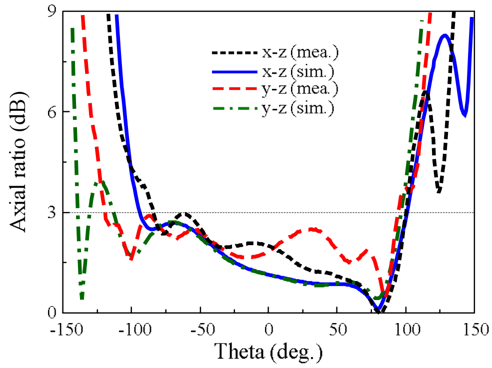


(b)

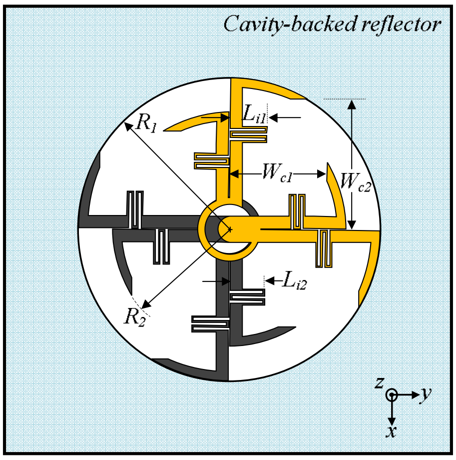
Fig. 6. Crossed scythe-shaped dipole antenna (a) radiation patterns and (b) axial ratio versus theta angle at 1.58 GHz. RHCP = right-hand circularly polarized, LHCP = left-hand circularly polarized.

standard GCS35M were used for the reflection coefficient measurement of the prototype in Fig. 5(a). The measured and simulated reflection coefficients for the proposed antenna are compared in Fig. 5(b). The measured bandwidth for the −10 dB reflection coefficient was 1.462−1.858 GHz. These values agreed rather closely with the simulated bandwidth of 1.475−1.835 GHz. The radiation patterns were measured in a full anechoic chamber with dimensions of 15.2 m (W) × 7.9 m (L) × 7.9 m (H). The simulated and measured AR values of the proposed antenna are shown in Fig. 5(c); good agreement was found between the two. The measured 3-dB AR bandwidth was 1.530−1.595 GHz with the CP center frequency at 1.575 GHz (AR of 1.6 dB), and the simulated 3-dB AR bandwidth was 1.530 −1.615 GHz with the CP center frequency of 1.58 GHz (AR of 0.93 dB). The impedance matching and 3-dB AR bandwidths of the proposed antenna completely cover the GPS L1, GLONASS L1, Galileo E1, and Compass B1 bands.

Fig. 6(a) shows the 1.58 GHz radiation patterns of the antenna with RHCP, the symmetrical profile, and the wide beamwidth in both the x−z and y−z planes. The measurements resulted in a gain of 7.53 dBic, a front-to-back ratio of 23.7 dB, and half-power beamwidths of 107° and 108° in the x−z and y−z planes, respectively. Fig. 6(b) shows the simulated and measured AR values of the antenna versus the theta angle at 1.58 GHz, with a very wide CP radiation beamwidth. The measured beamwidths for AR < 3 dB were 182° and 212° in the x−z and y−z planes, respectively. Additionally, the measurements showed a high radiation efficiency of 95.4%, which closely agrees with the simulated value of 97.5% at 1.58 GHz.

IV. Composite Cavity-Backed Crossed Two-Branch Scythe-Shaped Dipole

An additional resonance at 1.28 GHz was produced by adding a longer branch to the arm of the scythe-shaped



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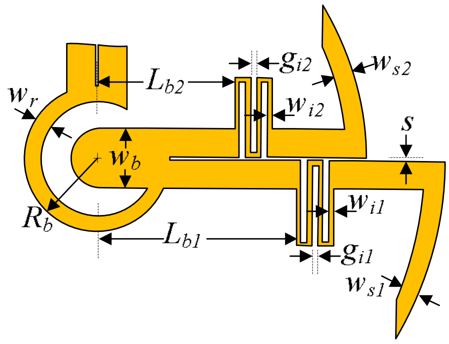

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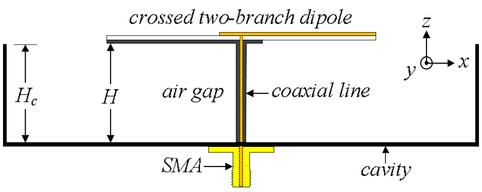


(c)

Fig. 7. Geometry of the proposed antenna. (a) Top view, (b) two-branch scythe-shaped dipole arm with vacant-quarter printed ring, and (c) side view.

dipole, as shown in Fig. 7. A rectangular cavity with basic dimensions of 120 mm × 120 mm and a height of H_c = 40 mm was also utilized as the reflector, to render a unidirectional radiation pattern with a wide beamwidth and a high front-to-back ratio at both bands. The optimized design parameters of the two-branch scythe-shaped dipole antenna were chosen for broadband characteristics and CP center frequencies at 1.28 and 1.58 GHz. They were: R_1 = 32.5 mm, R_2 = 25 mm, W_{c1} = 28 mm, W_{c2} = 21 mm, R_b = 6.6 mm, W_r = 1.4 mm, W_b = 5.4 mm, L_{b1} = 19 mm, L_{b2} = 13 mm, L_{i1} = 8 mm, L_{i2} = 7.4 mm, g_{i1} = 0.6 mm, w_{i1} = 0.4 mm, g_{i2} = 0.4 mm, w_{i2} = 0.4 mm, W_{s1} = 1.6 mm, W_{s2} = 1.6 mm, S = 0.4 mm, H_c = 40 mm, and H = 40 mm.

Each branch of the two-branch scythe-shaped dipole arm was confirmed to work separately on each desired bands by calculating the current distribution on the radiator of the dual-band antenna at 1.28 and 1.58 GHz. These results are presented in Fig. 8 with the phase angles, 0° and 90°. The large and small branches worked for the lower and higher bands, respectively. Additionally, for both frequencies, the x-axis oriented dipole arms worked at the phase angle of 0°, and the y-axis oriented dipole arms worked at the phase angle of 90°. These results indicate the good CP behavior of the proposed dual-band antenna.

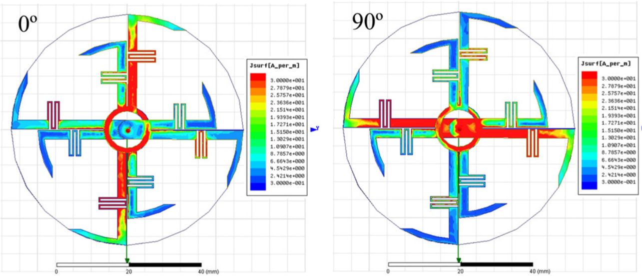
As shown in Table 2, which shows the performance characteristics of the crossed two-branch scythe-shaped dipole for different cavity heights (H_c), the cavity-backed reflector can also be used to improve the CP radiation beamwidth in dual-band operations. As the H_c increased, the impedance bandwidth for a −10 dB reflection coefficient scarcely changed in either band. However, the 3-dB AR bandwidth and beamwidth significantly improved, as shown in Table 2.

The HFSS simulations showed that the antenna yielded AR > 3 dB in both bands with the planar reflector (the antenna with H_c = 0 mm). The AR value was > 3 dB at the lower band for the case where H_c < 15 mm. The AR value was > 3 dB at the upper band when H_c < 17 mm. The

Table 2. Performance characteristics of the dual-band antenna for different cavity heights

H_c (mm)	Operating band	Impedance bandwidth (GHz)	3-dB AR bandwidth (GHz)	CP center frequency (GHz)	3-dB AR beamwidth at the CP center frequency (°)	
					x−z plane	y−z plane
0	Lower	1.240−1.410	0	1.320	0	0
	Upper	1.560−1.685	0	1.590	0	0
20	Lower	1.235−1.410	1.270−1.300	1.285	75	115
	Upper	1.555−1.665	1.585−1.600	1.590	85	119
40	Lower	1.220−1.385	1.260−1.300	1.280	168	150
	Upper	1.555−1.665	1.565−1.595	1.580	200	199

AR = axial ratio, CP = circularly polarized.



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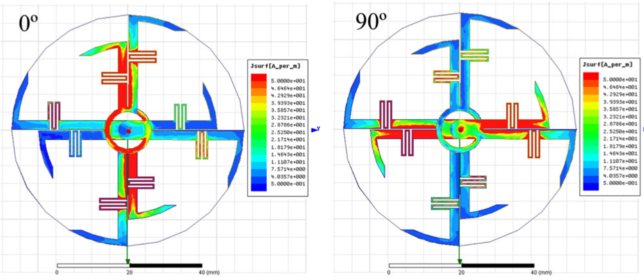
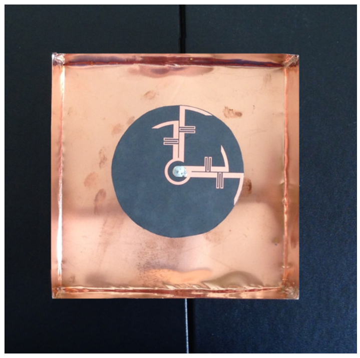


(b)

Fig. 8. Simulated current distributions on the crossed two-branch scythe-shaped dipole at (a) 1.28 GHz and (b) 1.58 GHz, for two phase angles of 0° and 90°.



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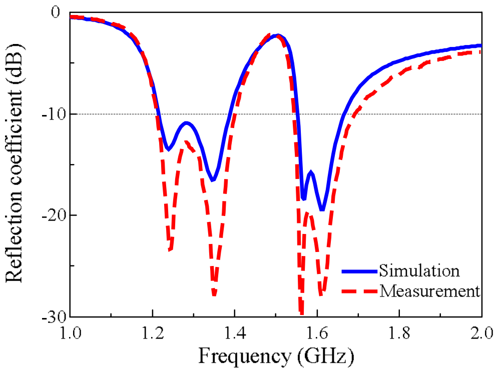

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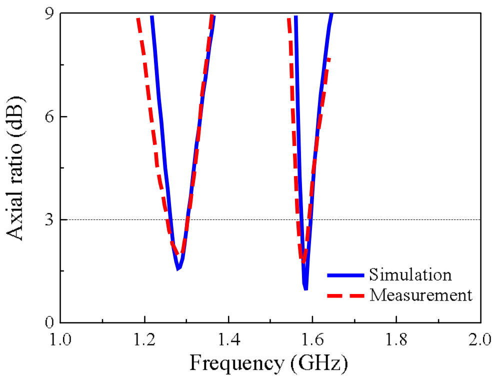

(c)

Fig. 9. (a) Top-view of a fabricated dual-band composite cavity-backed crossed scythe-shaped dipole antenna. Comparison of the simulated and measured (a) reflection coefficient and (c) axial ratio values.

case with $H_c = 20$ mm produced a 3-dB AR beamwidth $< 120°$ in both bands, whereas the case with $H_c = 40$ mm produced a 3-dB AR beamwidth $> 150°$ and 190° in the lower and upper bands, respectively.

The proposed dual-band antenna with $H_c = 40$ mm was also fabricated and measured. Fig. 9(b) compares the simulated and measured reflection coefficients of the prototype shown in Fig. 9(a). The measured impedance bandwidths for the −10 dB reflection coefficient were 1.218−1.400 GHz and 1.547−1.700 GHz, values that agree rather closely with the simulated bandwidths of 1.220−1.385 GHz and 1.555−1.665 GHz. Fig. 9(c) compares the simulated and measured AR values of the dual-band antenna; good agreement between the two can be observed. The measured 3-dB AR bandwidths were 1.255−1.300 GHz and 1.560−1.590 GHz, and the simulated 3-dB AR bandwidths were 1.260−1.300 GHz and 1.565−1.595 GHz. In addition, the measurement yielded CP center frequencies for the lower and upper bands of 1.28 and 1.575 GHz, with an AR of 1.7 and 1.86 dB, respectively. The impedance matching and 3-dB AR bandwidths of the proposed dual-band antenna completely cover the GPS L1, GLONASS L1, Compass B1, Galileo E1 and E6 bands.

Figs. 10 and 11 show the radiation patterns and AR values as functions of the theta angle for the dual-band antenna at 1.28 and 1.58 GHz, respectively. The measurements agreed well with the HFSS simulation results and showed RHCP radiation, a wide CP radiation beamwidth, and a symmetric pattern in both the x−z and y−z planes. At 1.28 GHz, the measurements resulted in a gain of 6 dBic, a front-to-back ratio of 24 dB, and a 3-dB AR beamwidth of 168° and 150° in the x−z and y−z planes, respectively. At 1.58 GHz, the measurements resulted in a gain of 5.9 dBic, a front-to-back ratio of 24 dB, and a 3-dB AR beamwidth of 200° and 199° in the x−z and y−z planes, respectively. Additionally, the measured radiation efficiencies were 90.4% and 87.6%, and the simulated values were 95.4% and 89.4%, at 1.28 GHz and 1.58 GHz, respectively.

V. Conclusion

Wide beamwidth CP composite cavity-backed crossed

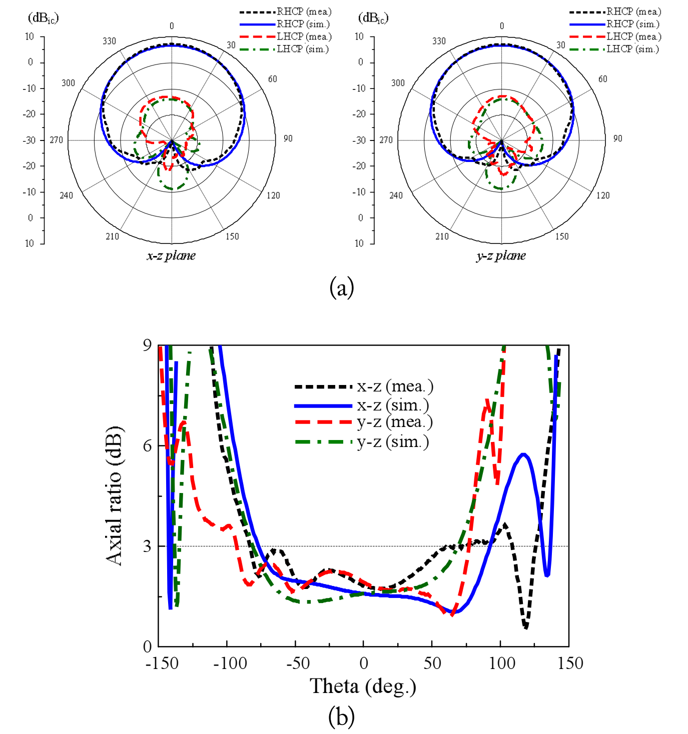

Fig. 10. Measurement and simulation. (a) Radiation patterns and (b) axial ratio versus theta angle at 1.280 GHz. RHCP = right-hand circularly polarized, LHCP = left-hand circularly polarized.

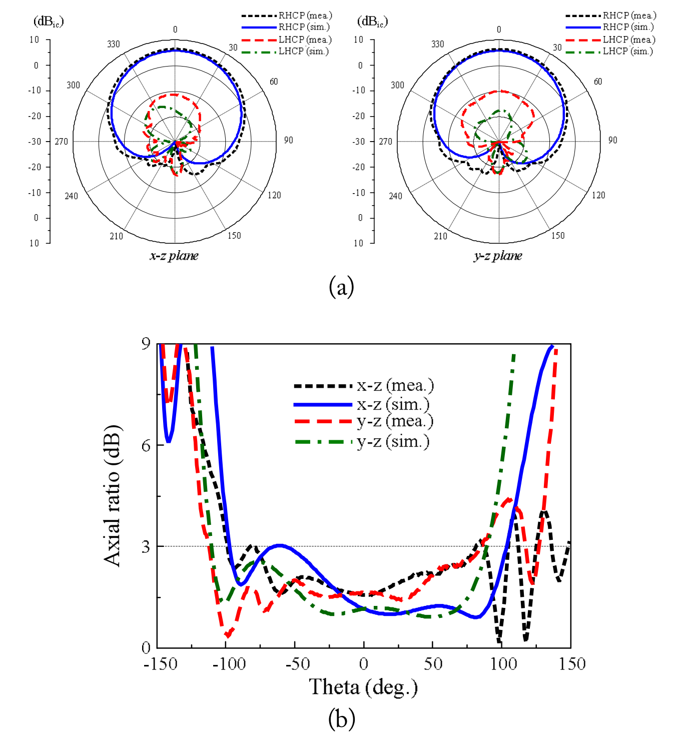

Fig. 11. Measurement and simulation. (a) Radiation patterns and (b) axial ratio versus theta angle at 1.580 GHz. RHCP = right-hand circularly polarized, LHCP = left-hand circularly polarized.

scythe-shaped dipoles were introduced for single- and dual-band operations. The scythe-shape dipoles with meander lines resulted in a reduction of the radiator sizes. The achieve CP radiation was achieve using a vacant-quarter printed ring with broadband impedance matching characteristics as the 90° phase delay line. The CP radiation was improved by the use of the composite scythe-shaped dipoles and a cavity-backed reflector. The proposed single-band antenna yielded bandwidths of 1.462 – 1.858 GHz for a − 10 dB reflection coefficient and 1.530 – 1.595 GHz for a 3-dB AR, in addition to a very wide CP radiation beamwidth (> 190°). The proposed dual-band antenna yielded bandwidths of 1.218 – 1.400 GHz and 1.547 – 1.700 GHz for the − 10 dB reflection coefficient and 1.255 – 1.300 GHz and 1.560 – 1.590 GHz for a 3-dB AR, in addition to a wide CP radiation beamwidth (> 160°) in both bands.

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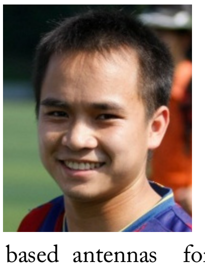
Son Xuat Ta



received the B.S. degree in electronics and telecommunications from Hanoi University of Science and Technology, Hanoi, Vietnam in 2008. He is currently studying a Ph.D. course in the Department of Electrical and Computer Engineering, Ajou University, Suwon, Korea. His research is focused on widebands, multiband, circularly polarized, and metamaterial-based antennas for next generation wireless communication systems.

Jae Jin Han

received the B.S. degree in electronics engineering from Korea Polytechnic University, Siheung, Korea in 2006, and the M.S. degree in electrical engineering from Ajou University, Suwon, Korea in 2008. He is currently studying a Ph.D. course in the Department of Electrical and Computer Engineering, Ajou University, Suwon, Korea and working for R&D division of DANAM Systems Inc., Anyang, Korea. His researches are focused on the antennas and RF devices.

Ikmo Park

received the B.S. degree in Electrical Engineering from the State University of New York at Stony Brook, and M.S. and Ph.D. degrees in Electrical Engineering from the University of Illinois at Urbana-Champaign. He joined the Department of Electrical and Computer Engineering at Ajou University in March, 1996. Prior to joining Ajou University, he has been working with the Device & Materials Laboratory of LG Corporate Institute of Technology, Seoul, Korea, where he had been engaged in research and development of various antennas for personal communication systems, wireless local area networks, and direct broadcasting systems. He was a Visiting Professor with the Department of Electrical and Computer Engineering, POSTECH, Pohang, Korea, from March 2004 to February 2005, and the Department of Electrical and Computer Engineering, University of Arizona, Tucson, Arizona, USA, from July 2011 to June 2012. He has authored and co-authored over 200 technical journal and conference papers. He also holds over 30 patents. He served as a Chair of the Department of Electrical and Computer Engineering at Ajou University. He is currently a member of Board of Directors in Korea Institute of Electromagnetic Engineering and Science Society and an Editor-in-Chief of the Proceedings of the Korea Institute of Electromagnetic Engineering and Science. His current research interests include the design and analysis of microwave, millimeter-wave, terahertz wave, and nano-structured antennas. He is also a member of Eta Kappa Nu and Tau Beta Pi.

Richard W. Ziolkowski

(ScB 1974, Brown University, MS'75 and PhD '80 from the University of Illinois at Urbana-Champaign, all in Physics) is the Litton Industries John M. Leonis Distinguished Professor in the Department of Electrical and Computer Engineering at the University of Arizona. He is also a Professor in the College of Optical Sciences at the University of Arizona. He was awarded an Honorary Doctorate, Doctor Technish Honoris Causa, from the Technical University of Denmark (DTU) in April 2012. He was the Computational Electronics and Electromagnetics Thrust Area Leader in the Engineering Research Division at the Lawrence Livermore National Laboratory before joining the University of Arizona in 1990. Professor Ziolkowski is a Fellow of both the Institute of Electrical and Electronics Engineers (IEEE) and the Optical Society of America (OSA). He served as the President of the IEEE Antennas and Propagation Society in 2005. He is also actively involved with the URSI, OSA and SPIE professional societies. He and Prof. Nader Engheta, University of Pennsylvania, are Co-Editors of the best-selling 2006 IEEE-Wiley book, Metamaterials: Physics and Engineering Explorations.