Progress In Electromagnetics Research C, Vol. 77, 1–9, 2017

Low Profile Broadband Antenna Array for High-Rate Close Proximity Wireless Communication Systems at 60 GHz

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Abstract—A broadband right-hand circularly polarized (RHCP) cross-type traveling wave antenna array is proposed for High-Rate Close Proximity (HRCP) point-to-point (P2P) wireless communication system at 60 GHz. Instead of low temperature co-fired ceramic (LTCC) technology, a single-layer structure of the proposed 2×1 element antenna array is fabricated with a conventional printed circuit board (PCB) process, to provide low manufacturing cost and low profile ($0.05\lambda_0$ at 60 GHz). A wide impedance bandwidth (57-64 GHz, VSWR < 2) and broad RHCP bandwidth (57–64 GHz, axial ratio (AR) < 3 dB) are achieved. The RHCP gain is higher than 6 dBic in the entire operating frequency band (57–64 GHz).

1. INTRODUCTION

Recently, the IEEE 802.15 Study Group 3e has been started to define the standard of a High-Rate Close Proximity (HRCP) point-to-point (P2P) wireless communication system at 60 GHz, which enables large files to be exchanged rapidly between two devices at very close range. The HRCP P2P wireless communication system, which uses a wide unlicensed frequency band around 60 GHz (57–64 GHz), has attracted great attention to provide high data rates (3.5 Gbps) for short-range communications within 10 cm ($\approx$ 4 inches) [1–3]. Considering gain, operating frequency bandwidth, technological reliability, and manufacturing cost, the design of millimeter-wave (mm-wave) antennas around 60 GHz has an important role in improving wireless communication link quality. Several antennas have been studied for 60-GHz applications, and they were implemented in multilayer structures, using low temperature co-fired ceramic (LTCC) technology [4–7]. The LTCC manufacturing process has the advantages of high reliability pattern on each layer, and low line loss in designing RF components, including antennas. This process, however, results in high manufacturing cost, due to the complex fabrication process with increased antenna volume. To realize successful development and commercialization of antennas for mm-wave applications, a low profile and single-layer antenna structure has been studied with conventional printed circuit board (PCB) technology [8, 9]. Although conventional PCB technology can achieve low cost and low profile mm-wave antennas around 60 GHz, it provide a narrow impedance bandwidth and low radiation efficiency, compared with LTCC technology.

In this paper, a broadband traveling wave antenna array is proposed for a HRCP P2P wireless communication system around 60 GHz (57–64 GHz). The proposed antenna array is designed by using the single-layer conventional PCB manufacturing process, to provide low manufacturing cost and a low profile. The proposed antenna element is designed as a right-hand circularly polarized (RHCP) cross-type traveling wave antenna, which is based on our previous study for tri-band GPS applications [10], to achieve broad RHCP bandwidth (AR < 3 dB). A 2×1 element antenna array is designed to enhance gain. The proposed RHCP cross-type traveling wave antenna array gives a wide impedance bandwidth (VSWR < 2), high RHCP gain (> 6 dBic), and a wide RHCP bandwidth (AR < 3 dB) within a compact volume (23.6 mm × 27.0 mm × 0.254 mm).

Received 30 June 2017, Accepted 8 August 2017, Scheduled 15 August 2017

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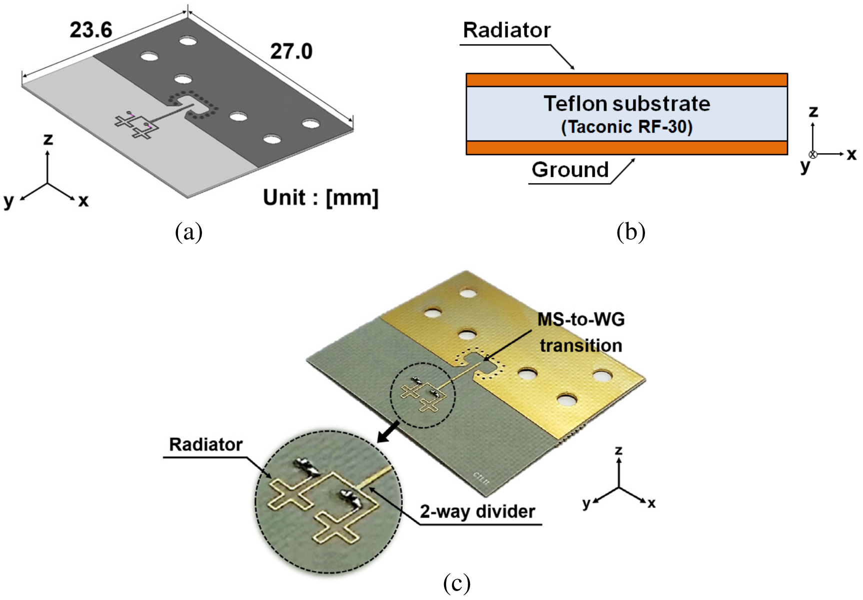
2. ANTENNA CONFIGURATION AND DESIGN CONCEPT

Figure 1 shows the overall structure of the proposed RHCP cross-type traveling wave antenna array. The overall size is 23.6 mm × 27.0 mm × 0.254 mm. It consists of a 2 × 1 cross-type traveling wave antenna element array, a 2-way divider, and a microstrip line (MSL) to waveguide (WG) transition. Fig. 1(c) shows a photograph of the fabricated proposed antenna array, using the single-layer conventional PCB manufacturing process, to provide low manufacturing cost and low profile. Taconic RF-30 ($\varepsilon_r = 2.9$, and $\tan\delta = 0.002$ at 60 GHz) is broadly used due to its low cost, an exceptionally low dissipation factor, and an enhanced surface smoothness in mm-wave frequency bands. The line width of the radiator of proposed antenna is 100 µm, and thickness of the metal is 40 µm.



(a) (b)
(c)

Figure 1. Structure of the proposed antenna: (a) overall view, (b) side view, and (c) photograph of fabricated antenna.

Figure 2 shows the detailed geometry and dimensions of the proposed antenna array mounted on a single layer of Taconic RF-30 substrate. It consists of two cross-type traveling wave antenna elements, a 2-way divider, a tapered microstrip line, and a microstrip line (MS) to the WR-15 waveguide (WG) transition. To achieve a wide impedance bandwidth with single-layer structure, the proposed antenna is designed using a traveling wave antenna structure. A traveling wave antenna, which can be created by using matched loads at the ends to prevent reflections, gives a wide impedance bandwidth [11]. To match a load impedance (200 Ω chip resistor) at the ends in the proposed antenna, the impedance formula of the two-wire transmission line is used. A 200 Ω resistor chip (0603 size) is mounted on the substrate through a via (diameter = 0.3 mm) toward a ground. To additionally achieve the right-hand circular polarization (RHCP) in the wide frequency bandwidth, the proposed antenna element is designed by using a cross-type traveling wave antenna structure [10]. The proposed cross-type traveling wave antenna array can achieve a wide impedance bandwidth (VSWR < 2) and wide RHCP bandwidth (AR < 3 dB) in the entire operating frequency band (57–64 GHz) of the HRCP P2P wireless communication system.

Figure 3 shows the electrical length of the proposed single element at 60 GHz. The length of each arm of the cross-type traveling wave antenna element is $1/4\lambda_g$ (λ_g: guided wavelength). The length of the 90° phase delay line ($D_{line\ 1,\ 2,\ 3,\ \text{and}\ 4}$), which is added to achieve the RHCP, is $1/4\lambda_g$. The total length of the proposed single element is $3\lambda_g$. Fig. 4 demonstrates how the proposed antenna generates the RHCP by showing the current distributions on the proposed traveling wave antenna element at 60 GHz. At 0° in phase, the total radiation field consists only of the radiation from the vertical segments since radiated fields of the horizontal segments cancel each other out, as shown in Fig. 4(a). The polarity of the total radiation field will be oriented upwards. At −90° in phase, the

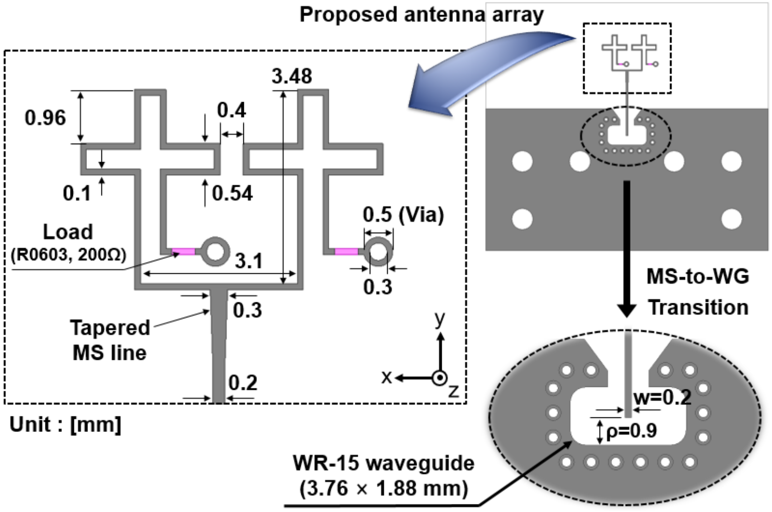


Figure 2. Detailed geometry and dimensions of the proposed antenna.

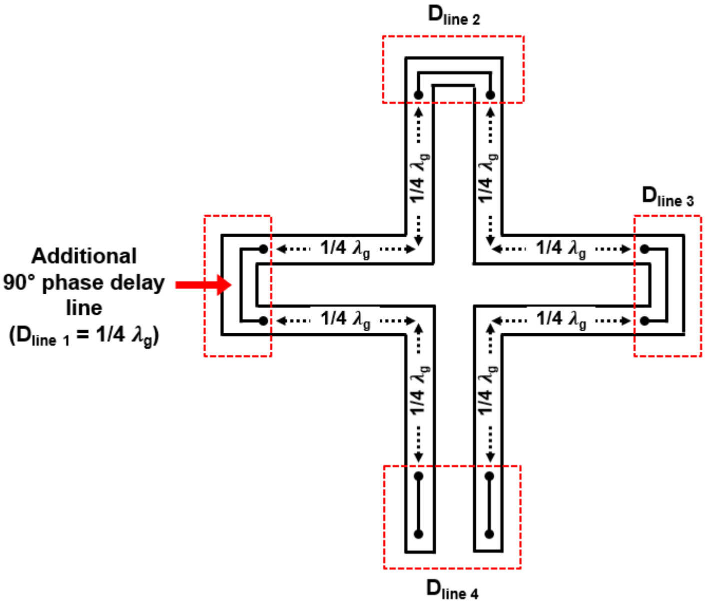


Figure 3. Electrical length of the proposed single element at 60 GHz.

total radiation field will have horizontal left-oriented polarity due to the current cancelation of vertical segments as shown in Fig. 4(b). Similarly, at $-180°$ and $-270°$ in phase, the polarity of the total radiation field will be oriented downward or to the right as shown in Figs. 4(c) and (d), respectively. Therefore, the proposed antenna can achieve the RHCP and provide a higher RHCP gain by using the 4 arms of the line array.

Figure 5 shows the simulated current distribution of the proposed traveling wave antenna array at 60 GHz. Simulated results are obtained using the SPEAG's SEMCAD X. It is observed that the proposed antenna array operates as an RHCP antenna.

Generally, the radiation pattern of an antenna at 60 GHz is measured by a far-field radiation measurement setup with the probe station system. This results in a high measurement setup cost. In this paper, a wideband microstrip line (MSL) to the back-short waveguide (WG) transition [12, 13] is designed to easily measure the radiation pattern of the proposed antenna array in the anechoic chamber, without the probe station setup. Fig. 6 shows the structure of the proposed wideband MSL to back-

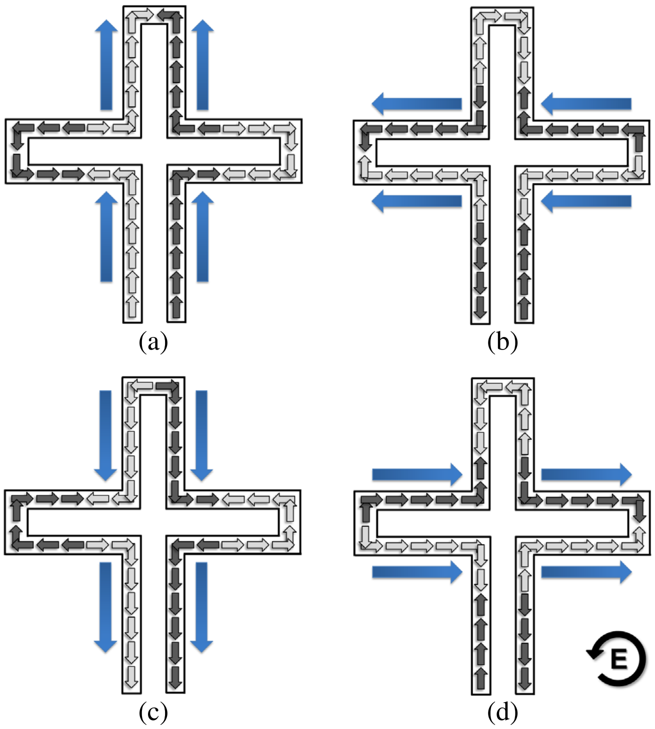


Figure 4. Current distributions on the proposed traveling wave antenna element at 60 GHz: (a) 0° in phase, (b) −90° in phase, (c) −180° in phase, and (d) −270° in phase.

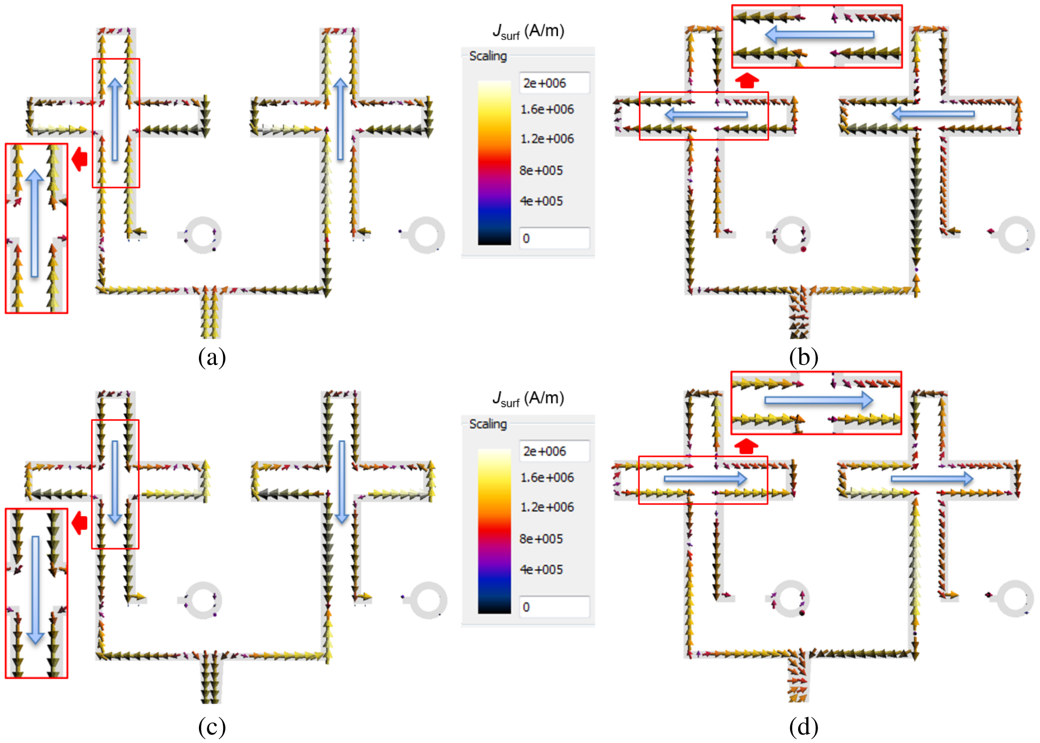


Figure 5. Simulated current distributions on the proposed traveling wave antenna array at 60 GHz: (a) 0° in phase, (b) −90° in phase, (c) −180° in phase, and (d) −270° in phase.

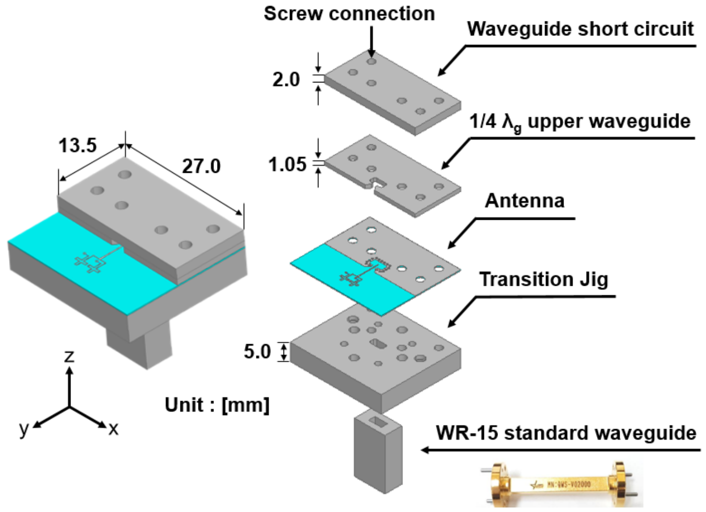
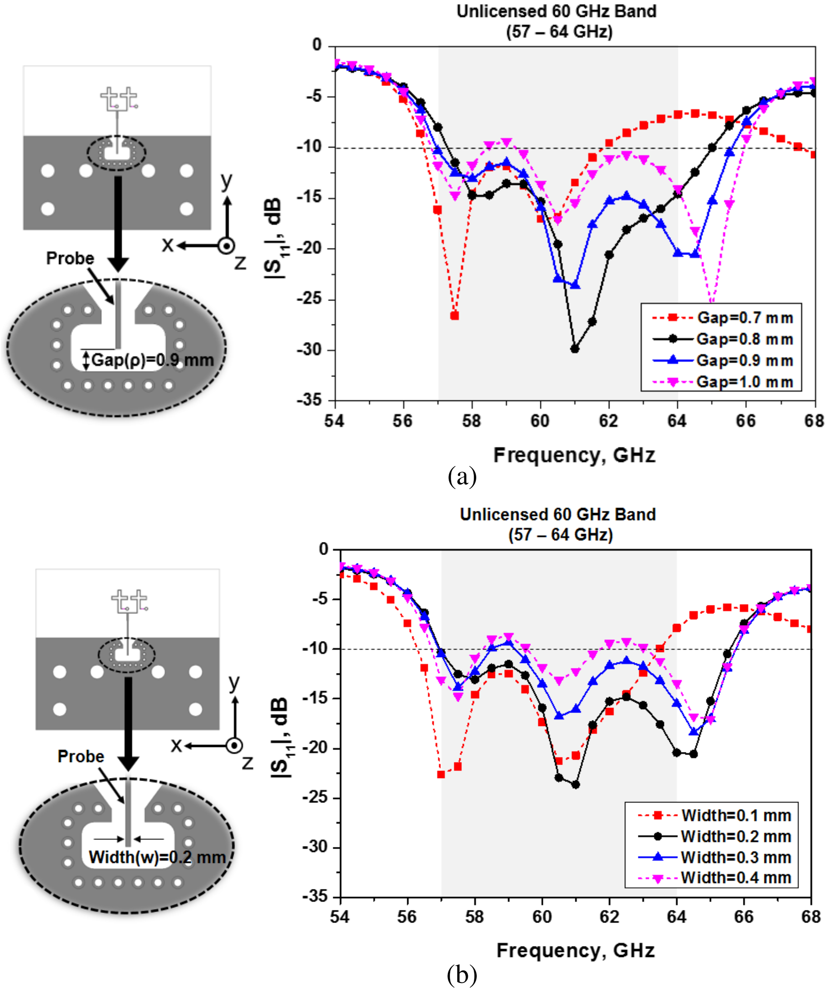


Figure 6. Structure of the proposed wideband MSL to back-short WG transition for connection between the waveguide and the antenna.



(a)

(b)

Figure 7. Simulated reflection coefficient of the proposed antenna with varying: (a)the gap (ρ) with the fixed probe width ($w = 0.2$) and (b) the probe width (w) with the fixed gap ($\rho = 0.9$).

short WG transition for connection between the waveguide and the antenna. It consists of a waveguide short circuit, a $1/4\lambda_g$ (1.05 mm at 60 GHz) upper waveguide, an antenna array, a transition jig, and a WR-15 standard waveguide (50–75 GHz).

To design optimal MSL to WG transition, the gap (ρ) between the WG conducting wall and the probe, and the probe width (w) should be optimized. Figs. 7(a) and (b) show the simulated reflection coefficients of the proposed antenna for different gaps ($\rho = 0.7 \sim 1.0\,\text{mm}$) with the fixed probe width ($w = 0.2\,\text{mm}$), and different probe widths ($w = 0.1 \sim 0.4\,\text{mm}$) with the fixed gap ($\rho = 0.9$). It is observed that the proposed antenna array, with the optimum value of the gap ($\rho = 0.9\,\text{mm}$) and the probe width ($w = 0.2\,\text{mm}$), can achieve wide impedance bandwidth (VSWR < 2) to cover the entire operating frequency band (57–64 GHz). Therefore, to measure antenna performance, the proposed antenna array is fabricated in conjunction with the MSL to back-short WG transition using a WR-15 standard waveguide as shown in Fig. 8.

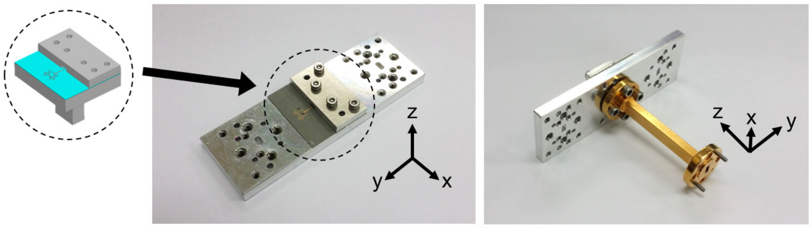


Figure 8. Photograph of the fabricated proposed antenna array with the MSL to back-short WG transition.

3. SIMULATED AND MEASURED RESULTS

Figure 9 shows the simulated and measured reflection coefficients (dB magnitude of S_{11}) of the proposed $2{\times}1$ element array. It can be seen that the proposed antenna array achieves a sufficiently wide impedance bandwidth (VSWR < 2) to cover the wide unlicensed frequency band around 60 GHz (57–64 GHz) for the HRCP P2P wireless communication system. Fig. 10 shows the simulated and measured AR of the proposed antenna array, and it shows that the AR is lower than 3 dB in the entire operating frequency band (57–64 GHz). When designing mm-wave antennas around 60 GHz, they result in high feed line loss

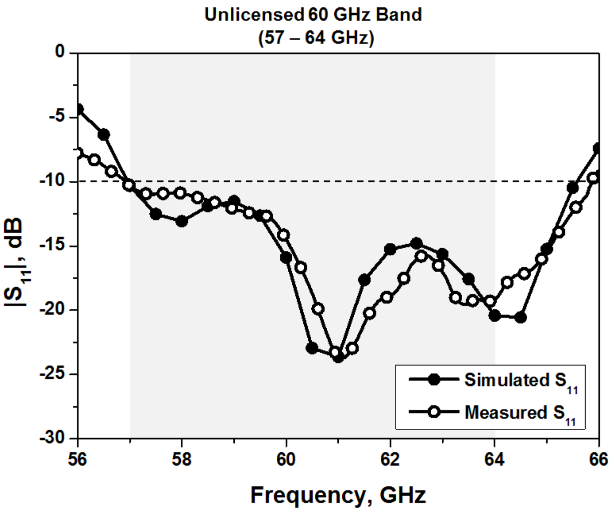


Figure 9. Simulated and measured reflection coefficients of the proposed antenna array.

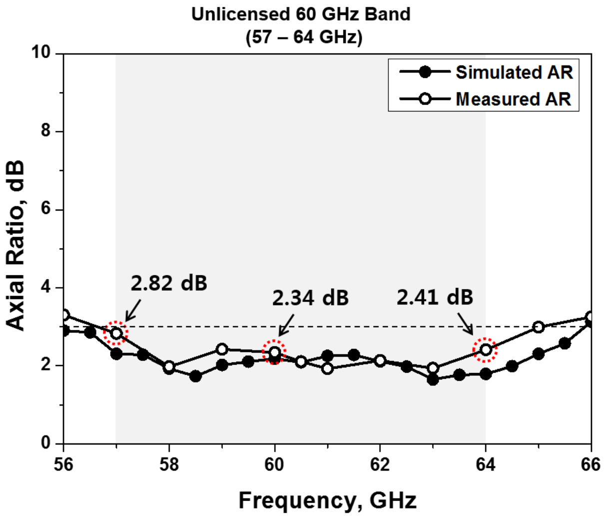


Figure 10. Simulated and measured axial ratios of the proposed antenna array.

and low radiation efficiency. Since the radiation efficiency of the proposed traveling wave antenna with the 4 arms is about 52%, a 2×1 element antenna array is designed to enhance gain (> 6 dBic). Fig. 11 shows that the simulated and measured RHCP gains are higher than 6 dBic in the entire operating frequency band (57–64 GHz). Fig. 12 shows the photograph of the measurement setup for the proposed antenna array. In this measurement, a WR-15 standard horn antenna and waveguide are used. Fig. 13 shows the simulated and measured radiation patterns on the xz-plane and yz-plane at 57, 60, and 64 GHz. The measured and simulated results agree well.

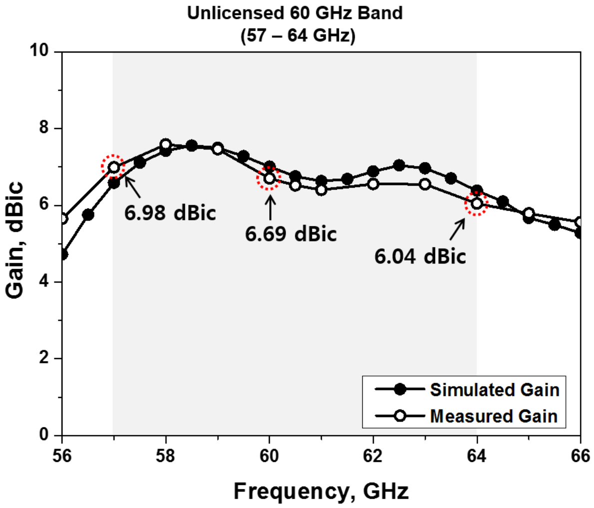


Figure 11. Simulated and measured gains of the proposed antenna array.

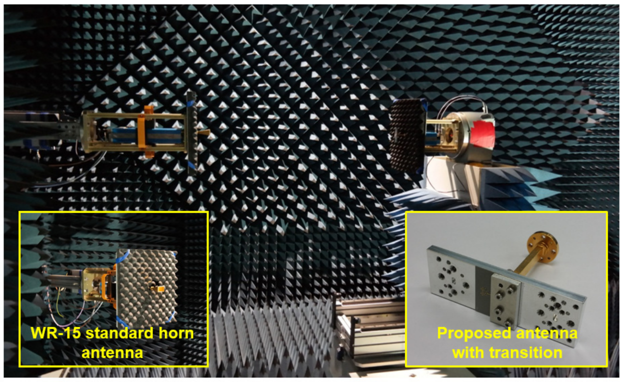
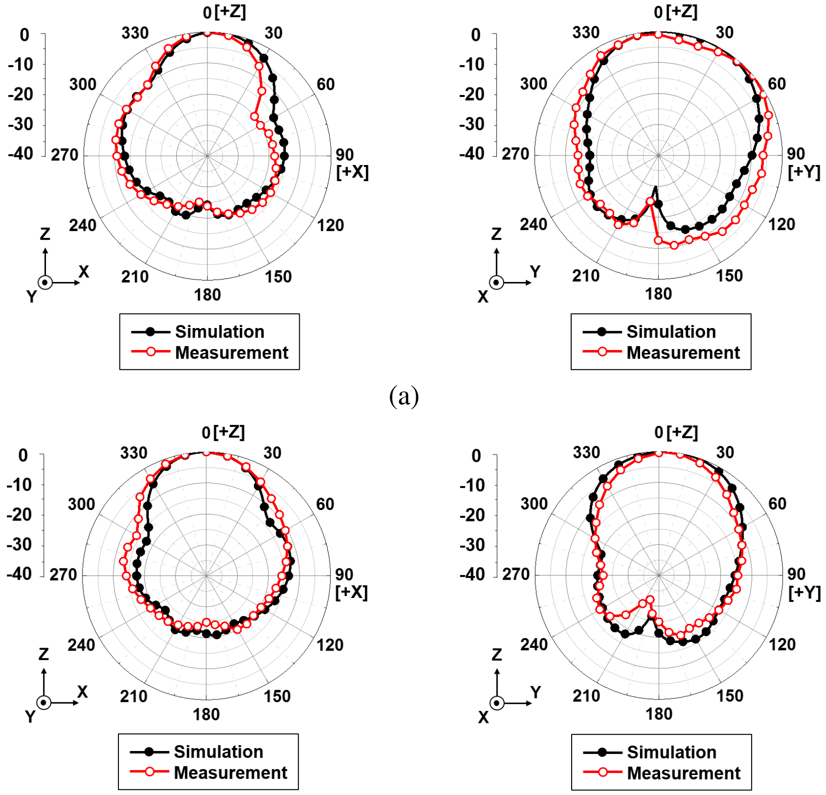
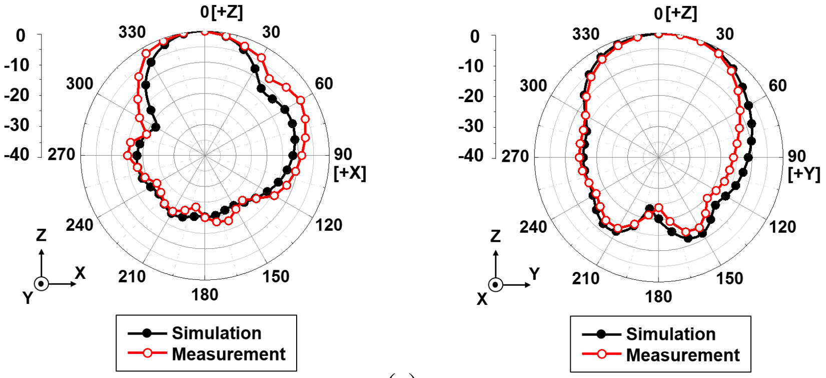


Figure 12. Photograph of measurement setup of proposed antenna with the connected back-short transition.



(a)

(b)



(c)

Figure 13. Radiation patterns (xz-plane and yz-plane) of the proposed antenna array: (a) at 57 GHz, (b) at 60 GHz, and (c) at 64 GHz.

4. CONCLUSION

A broadband RHCP cross-type traveling wave antenna array, which has low manufacturing cost and low profile (thickness = 0.254 mm, $0.05\lambda_0$ at 60 GHz), is proposed for the HRCP P2P wireless communication system. To achieve the low manufacturing cost and low profile, the proposed antenna array is designed on single-layer Teflon substrate (Taconic RF-30, $\varepsilon_r = 2.9$, $\tan\delta = 0.002$ at 60 GHz), using single-layer PCB technology. To achieve broad impedance bandwidth (VSWR < 2) and broad RHCP bandwidth (AR < 3 dB), and enhanced RHCP gain (> 6 dBic), with the single-layer structure, the proposed antenna is designed by using a cross-type traveling wave antenna structure. This proposed antenna array is therefore suitable for 60 GHz HRCP P2P wireless communication systems.

ACKNOWLEDGMENT

The present research has been conducted by the Research Grant of Kwangwoon University in 2016.

REFERENCES

1. Smulders, P., "Exploiting the 60 GHz band for local wireless multimedia access: prospects and future directions," *IEEE Commun. Mag.*, Vol. 40, No. 1, 140–147, Jan. 2002.
2. Wells, J., *Multi-Gigabit Microwave and Millimeter-Wave Wireless Communications*, Artech House, Norwood, MA, USA, 2010.
3. Li, Y. and K. M. Luk, "60-GHz substrate integrated waveguide fed cavity-backed aperture-coupled microstrip patch antenna arrays," *IEEE Trans. Antennas Propag.*, Vol. 63, No. 3, 1075–1085, Mar. 2015.
4. Lamminen, A., J. Säily, and A. Vimpari, "60-GHz patch antennas and arrays on LTCC with embedded-cavity substrates," *IEEE Trans. Antennas Propag.*, Vol. 56, No. 9, 2865–2874, Sep. 2008.
5. Xu, J., Z. N. Chen, X. Qing, and W. Hong, "Bandwidth enhancement for a 60 GHz substrate integrated waveguide fed cavity array antenna on LTCC," *IEEE Trans. Antennas Propag.*, Vol. 59, No. 3, 826–832, Mar. 2011.
6. Sun, H., Y. X. Guo, and Z. Wang, "60-GHz circularly polarized U-slot patch antenna array on LTCC," *IEEE Trans. Antennas Propag.*, Vol. 61, No. 1, 430–435, Jan. 2013.
7. Wang, L., Y. X. Guo, and W. X. Sheng, "Wideband high-gain 60-GHz LTCC L-probe patch antenna array with a soft surface," *IEEE Trans. Antennas Propag.*, Vol. 61, No. 4, 1802–1809, Apr. 2013.
8. Guntupalli, A. B. and K. Wu, "60-GHz circularly polarized antenna array made in low-cost fabrication process," *IEEE Antennas Wirel. Propag. Lett.*, Vol. 13, 864–867, Apr. 2014.

9. Li, M. and K. M. Luk, “A low-profile unidirectional printed antenna for millimeter-wave applications,” *IEEE Trans. Antennas Propag.*, Vol. 62, No. 3, 1232–1237, Mar. 2014.
10. Yoon, Y. and B. Lee, “A cavity-backed traveling wave antenna for tri-band GPS applications,” *IEEE Antennas Wirel. Propag. Lett.*, Vol. 15, 1454–1457, May 2016.
11. Balanis, C. A., *Antenna Theory: Analysis and Design*, Wiley, New York, NY, USA, 2005.
12. Ho, T. Q. and Y. C. Shih, “Spectral-domain analysis of E-plane waveguide to microstrip transitions,” *IEEE Trans. Microw. Theory Tech.*, Vol. 37, No. 2, 388–392, Feb. 1989.
13. Shih, Y. C., T. N. Ton, and L. Q. Bui, “Waveguide-to-microstrip transitions for millimeter-wave applications,” *IEEE MTT-S Int. Microwave Symp. Dig.*, 473–475, 1988.