

# Circularly Polarized Loop-Type Ground Radiation Antenna for IoT Applications

Zeeshan Zahid<sup>1</sup> · Longyue Qu<sup>2</sup> · Hyung-Hoon Kim<sup>3</sup> · Hyeongdong Kim<sup>2,\*</sup>

## Abstract

A circularly polarized loop-type ground radiation antenna using a ground mode tuning (GMT) structure is proposed for Internet of Things (IoT) devices. The antenna is designed to excite two orthogonal modes of equal magnitude on the ground plane. The GMT structure consists of an inductor and a metallic strip that has been installed at the edge of the ground plane to obtain a 90° phase shift between the two modes. The proposed antenna generates left-hand circularly polarized waves in the +z-direction and right-hand circularly polarized waves in the -z-direction. The antenna was fabricated to validate the simulation results. The measured -6 dB bandwidth of the antenna was 150 MHz and the axial ratio bandwidth with reference to 3 dB was 130 MHz, completely covering the 2.4–2.48 GHz band.

**Key Words:** Axial Ratio, Characteristic Modes, Circular Polarization, Reflection Coefficient.

## I. INTRODUCTION

Circularly polarized (CP) antennas are an attractive choice for wireless communication because of their reduced polarization loss factor and multi-path interference [1, 2]. Circular polarization is also a desirable feature in mobile devices for global positioning system applications [3, 4]. Moreover, we proposed a wideband CP monopole slot antenna using a square-shaped ground plane [5]. Electrically, small antennas of mobile devices suffer from several inherent problems, such as small bandwidth, high Q-factor, and low efficiency at smaller sizes [6, 7]. Therefore, small antennas are often employed to excite the large ground plane of a mobile device for effective radiation.

A loop-type ground radiation antenna (GradiAnt) showed good radiation performance in various studies [8–10]. The an-

tenna's performance is attributed to the antenna's strong coupling with the ground plane. Enhancing the radiation efficiency of mobile antennas is a challenging task for antenna engineers. To enhance the radiation efficiency of the antennas of a mobile device that has an electrically small ground plane, ground mode tuning (GMT) is an effective technique [11, 12]. The GMT structures are installed at the edge of the ground plane to match the resonance frequency of the ground mode with the operating frequency of the antenna [13]. The theory of characteristic modes can be utilized in a systematic design of antennas. Application of the theory to the design of CP antennas has been proposed in [14]. The loop-type GradiAnts proposed in the literature are linearly polarized antennas. However, GradiAnts with circular polarization are not well documented in the literature.

In this paper, we propose a CP loop-type GradiAnt for In-

Manuscript received November 28, 2018 ; Revised March 07, 2019 ; Accepted April 13, 2019. (ID No. 20181128-083J)

<sup>1</sup>Department of Electrical Engineering, Military College of Signals, National University of Sciences and Technology, Rawalpindi, Pakistan.

<sup>2</sup>Department of Electronics and Computer Engineering, Hanyang University, Seoul, Korea.

<sup>3</sup>Department of Cosmetic Science, Kwangju Women's University, Gwangju, Korea.

\*Corresponding Author: Hyeongdong Kim (e-mail: hdkim@hanyang.ac.kr)

This is an Open-Access article distributed under the terms of the Creative Commons Attribution Non-Commercial License (<http://creativecommons.org/licenses/by-nc/4.0>) which permits unrestricted non-commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

© Copyright The Korean Institute of Electromagnetic Engineering and Science. All Rights Reserved.

ternet of Things (IoT) devices with compact-sized ground plane, operating at 2.45 GHz. To generate CP waves, two orthogonal current modes of the ground plane need to be excited by the antenna with a phase difference of  $90^\circ$  [15]. Implementing these conditions on a mobile device antenna while maintaining good radiation efficiency is a challenging task. In the antenna design process, we have employed the characteristic mode analysis of the proposed ground plane. Two orthogonally polarized modes with equal magnitude have been excited by designing the antenna at the corner of the ground plane. The GMT structure is utilized to tune one of the modes so that a phase difference of  $90^\circ$  is achieved between the two modes. The mode can be fine-tuned by using different values of inductor.

## II. ANTENNA DESIGN

The loop-type GradiAnt acts as a magnetic coupler, and its coupling with the dominant ground mode is maximum when it is located at the maximum current location of the ground mode. Therefore, the optimum location of the antenna is at the middle of the edge of the ground plane. At this location, however, the antenna excites only one mode. To simultaneously excite two orthogonal modes on the ground plane with equal magnitude, the antenna should be located at the corner of the ground plane. At this location, the electric field of both modes is strongest; therefore, the electric coupling between the antenna and the ground modes should be enhanced. This can be expressed as [16]:

$$\alpha_e = \frac{1}{\omega_o^2 - \omega_g^2} \iiint \mathbf{J}^i \cdot \mathbf{E}^g d\tau \quad (1)$$

where  $\mathbf{J}^i$  is the impressed electric current density,  $\mathbf{E}^g$  is the electric field of the ground plane,  $\omega_o$  is the operating frequency of the antenna, and  $\omega_g$  is the resonance frequency of the ground mode. The integration is carried over the volume of the antenna. Furthermore, the coupling between the GradiAnt and the ground mode can be enhanced by the optimum impedance level of the antenna's resonance loop. The impedance level is expressed as  $(L_r/C_r)^{1/2}$ , where  $L_r$  is the inductance of the resonance loop and  $C_r$  is the resonance capacitor. The optimum impedance level depends on the antenna's location on the ground plane and the size of the antenna's resonance loop. If the antenna is located at the middle of the ground plane, the impedance level should be minimum, whereas if the antenna is located at the edge of the ground plane, the impedance level should be maximum [17]. The antenna's impedance level can be enhanced by increasing the clearance area of the antenna and using a lower value of  $C_r$ . The impedance matching can be controlled by the feeding loop that contains  $C_f$  [18]. The impedance level of the feeding loop  $(L_f/C_f)^{1/2}$  must be  $50 \Omega$  to match with the RF

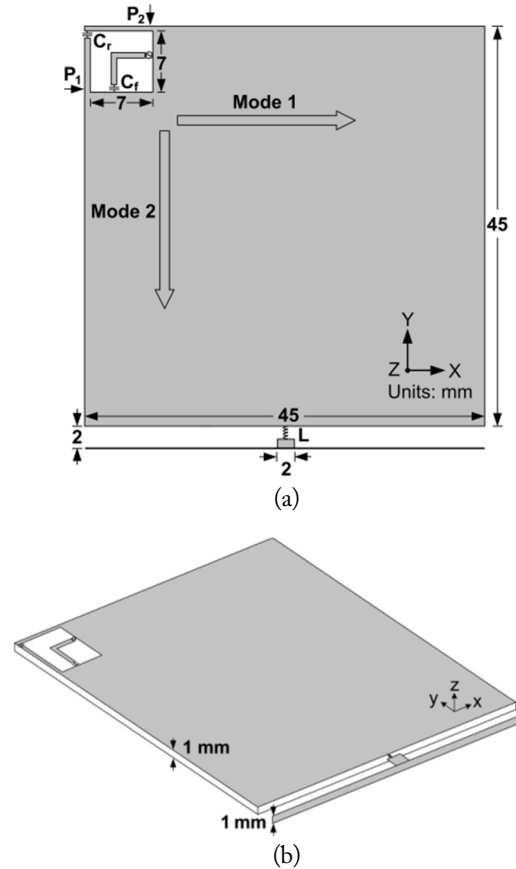


Fig. 1. Geometry of the proposed antenna with front view (a) and 3D view (b).

source. The operating frequency of the antenna is also determined by  $L_r$  and  $C_r$ . The geometry of the proposed antenna is shown in Fig. 1.

The antenna element is located at the left corner of the  $45 \text{ mm} \times 45 \text{ mm}$  ground plane by etching a square clearance of  $7 \text{ mm} \times 7 \text{ mm}$  in size. FR4 material ( $\epsilon_r = 4.4$ ,  $\tan\delta = 0.02$ ) with 1 mm thickness is used as a substrate material. The resonance capacitor ( $C_r$ ) is located at the corner of the outer loop, called the resonance loop. The feeding loop is  $4.5 \text{ mm} \times 4.5 \text{ mm}$  in size and contains the feeding capacitor  $C_f$ . The GMT structure is placed at the bottom of the ground plane and consists of an inductor ( $L$ ), a metallic strip  $45 \text{ mm} \times 1 \text{ mm}$  in size, and a shorting strip. The strip is oriented along the  $xz$ -plane, and the gap between the metallic strip and the ground plane is 2 mm. The strip is connected with the ground plane through the shorting strip and the inductor. The width of the shorting strip is 2 mm.

## III. SIMULATION RESULTS

The resonance capacitor's location on the resonance loop plays a critical role in the excitation of orthogonal modes on the ground [19]. When a low-valued  $C_r$  is located at  $P_1$  on the res-

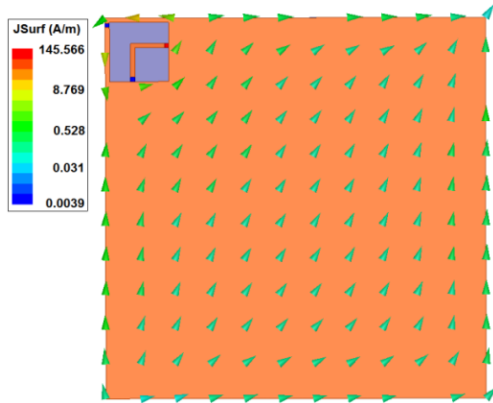


Fig. 2. Simulated current density of the antenna without the GMT structure.

onance loop, high reactance of the capacitor can be modeled as an open circuit; thereby the GradiAnt acts as a monopole antenna attached to the location  $P_2$ . Therefore, according to Eq. (1), the antenna excites the current along the x-axis (mode 1) on the ground plane. Similarly, the antenna excites the current along the y-axis (mode 2) on the ground plane when  $C_r$  is located at  $P_2$ . Placing  $C_r$  at the corner of the resonance loop virtually divides the antenna into two monopoles attached at  $P_1$  and  $P_2$ , respectively, resulting in the excitation of both modes with equal magnitude. Fig. 2 shows the simulated surface current density on the ground plane without the GMT structure. The simulated values of  $C_r$  and  $C_f$  were 0.15 pF and 0.12 pF, respectively, where the values have been optimized through full-wave simulations. It can be observed that the current is excited diagonally on the ground plane, which is the resultant direction of mode 1 and mode 2, demonstrating that both modes have been excited with equal magnitude.

To achieve circular polarization, the first two modes of the ground plane have been utilized, where  $\omega_g$  of both modes is greater than  $\omega_0$ . The GMT structure is employed to decrease the resonance frequency of mode 2, so that a phase difference of  $90^\circ$  is achieved between modes 1 and 2 while maintaining equal magnitude in both modes. The resonance frequencies of the ground modes depend on the size of the ground plane; therefore, the antenna performance depends critically on the ground plane size. Simulations have been conducted to observe the effect of the size of the ground plane on antenna performance where the sizes of the antenna and the GMT strip have been unchanged. The observations are shown in Table 1. The data demonstrate

Table 1. Effect of ground size on antenna performance

Ground size (mm <sup>2</sup> )	$f_g$ (GHz)	$f_0$ (GHz)	$L$ (nH)	Bandwidth (MHz)	
				Matching	Axial ratio
40 × 40	4.24	2.47	2	90	60
45 × 45	3.75	2.45	1.5	100	90
50 × 50	3.37	2.43	1	130	110

that the increase in the ground plane size decreases the resonance frequency of both ground modes ( $f_g$ ), as well as the operating frequency of the antenna ( $f_0$ ). The tabulated  $f_g$  is without GMT structure. The decrease in  $f_g$  is more significant as compared to  $f_0$ . The operating frequency can be tuned using  $C_r$ . Furthermore, it is observed that the antenna's matching bandwidth (-6 dB ref.) increases with the increase in the ground size. According to Eq. (1), the coupling between the antenna and the ground mode increases if  $\omega_g$  approaches  $\omega_0$ . The higher coupling results in the increased matching bandwidth of the antenna. To decrease the resonance frequency of mode 2 of the ground plane, inductor ( $L$ ) has been utilized, which appears in series with the ground mode. Therefore, increasing  $L$  decreases the resonance frequency of mode 2. Table 1 indicates that the lower values of  $L$  are used to achieve circular polarization with the increase in the ground size. Moreover, the axial ratio (AR) bandwidth increases with the increase in the ground size.

To validate the polarization of the antenna, the simulated surface current density of the proposed structure is presented in Fig. 3. Simulations show that the excited currents rotate in clockwise direction on the ground plane. Fig. 3(a) shows that the current density on the major portion of the ground plane is directed along the x-axis at a phase of  $0^\circ$ , i.e., mode 1 is domi-

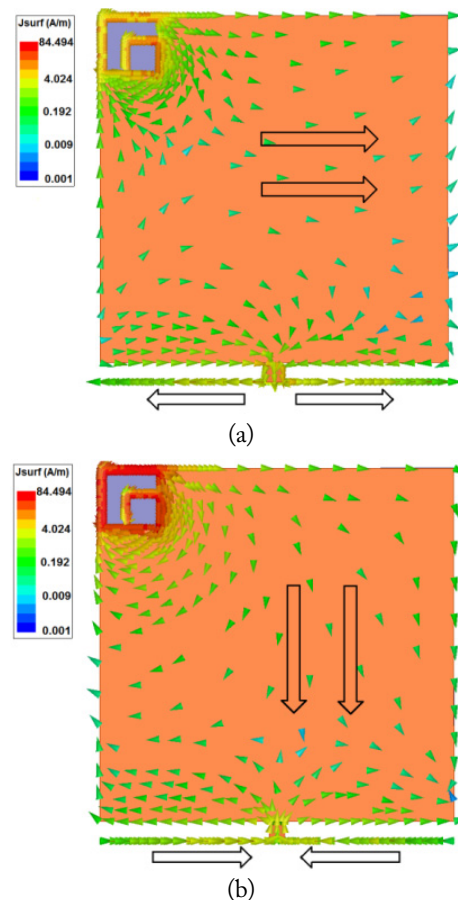


Fig. 3. Simulated surface current density at 2.45 GHz at the phase of  $0^\circ$  (a) and at the phase of  $90^\circ$  (b).

nant.

Similarly, Fig. 3(b) shows that, at the phase of  $90^\circ$ , the current is directed along the  $y$ -axis, i.e., mode 2 is dominant. It can be observed that the current density is stronger around the GradiAnt, showing that the antenna acts as an excitation element for the ground plane. Although the magnitude of current density around the antenna is strong, the current distribution on the ground plane produces effective radiation. Therefore, the time phase difference between both ground modes generates left-hand circularly polarized (LHCP) waves along the  $+z$ -axis and right-hand circularly polarized (RHCP) waves along the  $-z$ -axis.

#### IV. EXPERIMENTAL RESULTS AND DISCUSSION

The antenna was fabricated for experimental validation, as shown in Fig. 4. The reflection coefficient was measured using Agilent 8753ES vector network analyzer, and the radiation characteristics were measured using a 3D CTIA-OTA chamber. The measured and simulated reflection coefficients are presented in Fig. 5.

The simulated bandwidth of the antenna with reference to  $-6$  dB was 100 MHz (2.4–2.5 GHz), whereas the measured bandwidth was 150 MHz (2.37–2.52 GHz), showing good agreement with the simulated result. The measured and simulated ARs in the direction of  $+z$ -axis are plotted in Fig. 6 along with measured total efficiency. The measured AR bandwidth with

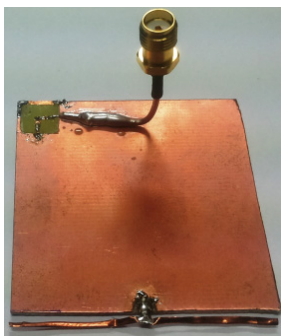


Fig. 4. Fabricated antenna.

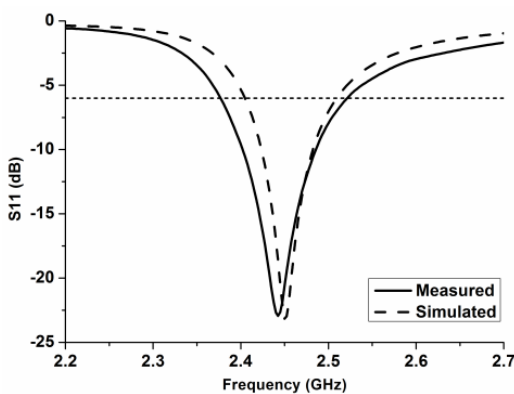


Fig. 5. Measured and simulated reflection coefficient of the antenna.

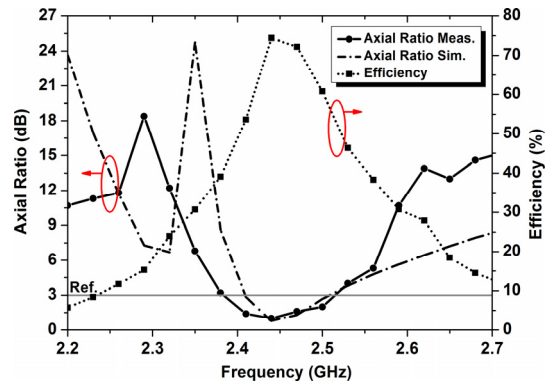


Fig. 6. Measured axial ratio and total efficiency of the antenna.

reference to 3 dB was 130 MHz (2.38–2.51 GHz) and the simulated AR was 90 MHz (2.41–2.5 GHz). The minimum value of measured AR was 1 dB at 2.44 GHz. The average efficiency of the antenna in the operating band is 65%, and the maximum efficiency of the antenna is 74% at 2.44 GHz. The efficiency of the antenna is suitable for wireless applications. Fig. 7 presents measured LHCP, RHCP, and peak gains as functions of frequency. In accordance with the measured efficiency, the maximum value of peak gain (1.66 dB) occurs at 2.45 GHz and decreases away from it. Measured LHCP and RHCP gains at the operating frequency are  $-0.36$  dB and  $0.64$  dB, respectively. The normalized, simulated, and measured radiation patterns of the antenna at 2.45 GHz are displayed in Figs. 8 and 9, respectively. The RHCP and LHCP data in the  $xz$ - and the  $yz$ -planes are plotted in Fig. 8. The difference between simulated and measured results is mainly due to the feeding cable and the fabrication tolerance of the GMT structure. As shown, the higher values of LHCP and RHCP gain patterns occur in the upper and lower hemispheres, respectively, confirming that the antenna produces LHCP and RHCP waves along the  $+z$ - and  $-z$ -axes, respectively. In Fig. 8(a), it can be observed that the LHCP and RHCP patterns in the  $xz$ -plane are symmetric, whereas in the  $yz$ -plane the patterns are tilted towards  $-30^\circ$  and  $-150^\circ$ , respectively. The asymmetry is due to the asymmetric geometry of the

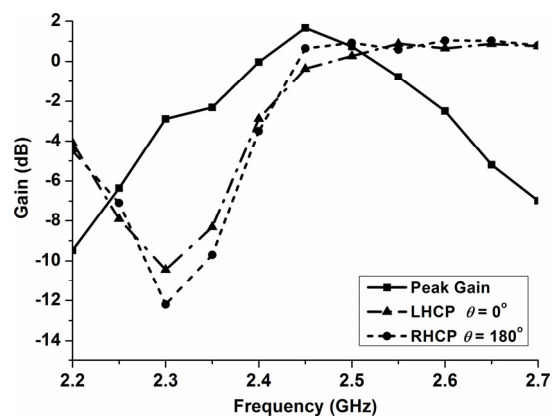


Fig. 7. Measured gains of the antenna as function of frequency.



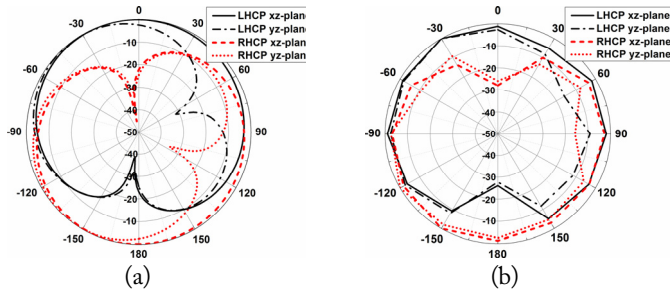


Fig. 8. LHCP and RHCP gains of the antenna: (a) simulated and (b) measured.

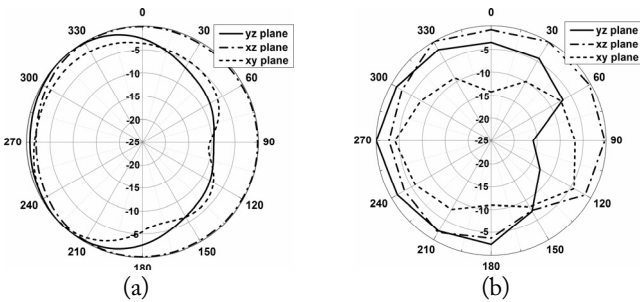


Fig. 9. Total gain of the antenna: (a) simulated and (b) measured.

proposed antenna where the GMT structure is installed in the  $yz$ -plane, whereas in the  $xz$ -plane there is no GMT structure. Moreover, as shown in Fig. 3, linear currents are excited in the GMT structure, causing the patterns to tilt in the  $yz$ -plane. The measured cross polarization levels of the antenna in  $+z$  and  $-z$  axes were below  $-25$  dB. The simulated total gain radiation pattern is shown in Fig. 9(a). The pattern is isotropic in the  $xz$ -plane, whereas in the  $xy$ -plane, the minimum value of the pattern is  $-10.5$  dBi, which occurs at  $90^\circ$ . Therefore, the antenna has a quasi-isotropic radiation pattern, suitable for wireless applications as compared to that of linearly polarized antennas having nulls in the radiation patterns [19]. A good agreement can be observed in the measured and simulated gain patterns in the  $xz$ - and  $yz$ -planes. The minimum value of the measured gain was  $-15.87$  dBi, in the  $yz$ -plane. The agreement of the measured and simulated results verifies that the proposed antenna is suitable for IoT applications.

## V. CONCLUSION

We proposed a CP loop-type ground radiation antenna using a ground mode tuning structure. The conditions of circular polarization were achieved successfully using the antenna design and ground mode tuning structure. The simulated and measured data showed good agreement. The antenna generated LHCP waves in the  $+z$ -axis and RHCP waves in the  $-z$ -axis with cross polarization levels less than  $-25$  dB. The total gain radiation pattern of the antenna was quasi-isotropic, which is an

attractive feature for internet of things applications. The matching bandwidth of the antenna was 150 MHz and the axial ratio bandwidth was 130 MHz, covering the complete 2.4–2.48 GHz band. The proposed technique is versatile and can be applied to other wireless applications as well.

## REFERENCES

- [1] M. A. Kossel, R. Kung, H. Benedickter, and W. Biichtokd, "An active tagging system using circular-polarization modulation," *IEEE Transactions on Microwave Theory and Techniques*, vol. 47, no. 12, pp. 2242–2248, 1999.
- [2] R. Garg, P. Bhartia, I. Bahl, and A. Ittipiboon, *Microstrip Antenna Design Handbook*. Norwood, MA: Artech House, 2001.
- [3] W. J. Liao, J. T. Yeh, and S. H. Chang, "Circularly polarized chip antenna design for GPS reception on handsets," *IEEE Transactions on Antennas and Propagation*, vol. 62, no. 7, pp. 3482–3489, 2014.
- [4] S. H. Chang and W. J. Liao, "A novel dual band circularly polarized GNSS antenna for handheld devices," *IEEE Transactions on Antennas and Propagation*, vol. 61, no. 2, pp. 555–562, 2013.
- [5] P. Mousavi, B. Miners, and O. Basir, "Wideband L-shaped circular polarized monopole slot antenna," *IEEE Antennas and Wireless Propagation Letters*, vol. 9, pp. 822–825, 2010.
- [6] H. Wheeler, "Small antennas," *IEEE Transactions on Antennas and Propagation*, vol. 23, no. 4, pp. 462–469, 1975.
- [7] R. F. Harrington, "Effect of antenna size on gain, bandwidth, and efficiency," *Journal of Research of the National Bureau of Standards D (Radio Propagation)*, vol. 64, no. 1, pp. 1–12, 1960.
- [8] O. Cho, H. Choi, and H. Kim, "Loop-type ground antenna using capacitor," *Electronics Letters*, vol. 47, no. 1, pp. 11–12, 2011.
- [9] Y. Liu, X. Lu, H. Jang, H. Choi, K. Jung, and H. Kim, "Loop-type ground antenna using resonated loop feeding, intended for mobile devices," *Electronics Letters*, vol. 47, no. 7, pp. 426–427, 2011.
- [10] H. C. Choi, J. Lee, O. Cho, H. Lee, and B. Park, "Ground radiation antenna," U.S. Patent 8604998, 2013.
- [11] L. Qu, R. Zhang, H. Shin, J. Kim, and H. Kim, "Performance enhancement of ground radiation antenna for Z-wave applications using tunable metal loads," *Electronics Letters*, vol. 52, no. 22, pp. 1827–1828, 2016.
- [12] L. Qu, R. Zhang, H. Shin, J. Kim, and H. Kim, "Mode-controlled wideband slot-fed ground radiation antenna utilizing metal loads for mobile applications," *IEEE Transactions on Antennas and Propagation*, vol. 65, no. 2, pp. 867–872, 2017.

- [13] Z. Zahid and H. Kim, "Enhancement technique for loop type ground radiation antenna using ground mode tuning structure," *Microwave and Optical Technology Letters*, vol. 59, no. 2, pp. 476-478, 2017.
- [14] M. Cabedo-Fabres, E. Antonino-Daviu, A. Valero-Nogueira, and M. F. Bataller, "The theory of characteristic modes revisited: a contribution to the design of antennas for modern applications," *IEEE Antennas and Propagation Magazine*, vol. 49, no. 5, pp. 52-68, 2007.
- [15] C. A. Balanis, *Antenna Theory: Analysis and Design*, 3rd ed. Hoboken, NJ: John Wiley & Sons, 2005.
- [16] R. F. Harrington, *Time-Harmonic Electromagnetic Fields*. New York, NY: Wiley-Interscience, 2001.
- [17] Z. Zahid and H. Kim, "Performance evaluation of loop-type ground radiation antenna based on its optimum impedance level," *Electronics Letters*, vol. 53, no. 7, pp. 446-448, 2017.
- [18] Z. Zahid and H. Kim, "Analysis of a loop type ground radiation antenna based on equivalent circuit model," *IET Microwaves, Antennas & Propagation*, vol. 11, no. 1, pp. 23-28, 2017.
- [19] R. Zhang, Y. Liu, and H. Kim, "Effect of capacitor position on radiation patterns of ground radiation antenna," *Electronics Letters*, vol. 51, no. 23, pp. 1844-1846, 2015.

### Zeeshan Zahid



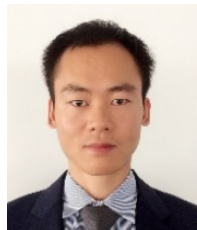
received his M.S. in Electronics from Quaid-i-Azam University, Islamabad, in 2006. He joined National University of Sciences and Technology (NUST) as a lecturer. He received Best Teacher of the Year award in 2012. He earned his Ph.D. in electronics and computer engineering from Hanyang University, Korea, in 2017. He is currently serving as an assistant professor at Military College of Signals, NUST. His research interests include MIMO antennas and circularly polarized antennas for mobile devices.

### Hyung-Hoon Kim



received his B.S. degree from Chonnam National University in 1986, M.S. from Korea Advanced Institute of Science and Technology in 1988, and his Ph.D. from Hanyang University in 1997. Since 1994, he has served as professor in the Department of Cosmetic Science at Kwangju Women's University, Korea. His research interest is electromagnetic numerical analysis.

### Longyue Qu



received his B.Sc. degree in communication engineering from Yanbian University, China, in 2013, and his M.Sc. and Ph.D. degrees in microwave engineering from Hanyang University, Seoul, Korea, in 2015 and 2018, respectively. He is currently a research fellow at Hanyang University. His current research interests include antenna theory and design especially for 4G/5G communications, massive

MIMO, metamaterials, mmWave, and RF circuits. He serves as a reviewer for several international journals, such as *IEEE Transactions on Antennas and Propagation*, *IEEE Antennas and Propagation Letters*, and *IEEE Access*.

### Hyeongdong Kim



received his B.S. and M.S. degrees from the Seoul National University, Seoul, Korea, in 1984 and 1986, respectively, and his Ph.D. degree from the University of Texas at Austin in 1992. From May 1992 to February 1993, he was a post-doctoral fellow at the University of Texas at Austin. In 1993, he worked as a professor at the Department of Electrical and Computer Engineering, Hanyang University, Seoul, Korea. His current research interests are various antenna theories and designs based on ground characteristic mode analysis, namely, wideband, high-efficiency, circular polarization, MIMO, and high-sensitivity antennas.