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A New Quadri-Polarization Reconfigurable Circular Patch Antenna

HUI GU[1], JIANPENG WANG[2], LEI GE[3], (Member, IEEE), and CHOW-YEN-DESMOND SIM[4], (Senior Member, IEEE)
[1]FN Design & Development Department, ZTE Corporation, Nanjing 210012, China
[2]Ministerial Key Laboratory of JGMT, Nanjing University of Science and Technology, Nanjing 210094, China
[3]College of Electronic Science and Technology, Shenzhen University, Shenzhen 518060, China
[4]Department of Electrical Engineering, Feng Chia University, Taichung 40724, Taiwan

Corresponding author: L. Ge (leige@szu.edu.cn)

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ABSTRACT A new probe-fed patch antenna with polarization reconfiguration is presented in this paper. The antenna is composed of a circular radiating patch and a switchable feed network. By controlling the operating states of four pairs of PIN diodes in the feed network, the feed point of the circular patch can be switched. Therefore, a reconfiguration between four linear polarization directions at a 45° interval (22.5°, 67.5°, 112.5°, and 157.5°) can be realized. All the different polarization states own similar matching and radiation characteristics. Simulated and measured results indicate that the antenna can achieve reconfigurable quadri-polarization diversity features with an invariable operating frequency and excellent radiation performance, which are very attractive for wireless communications. In addition, the proposed design can offer more reconfigurable linear polarization directions by adding more switchable paths in the feed network.

INDEX TERMS Reconfigurable antenna, patch antenna, PIN diode.

I. INTRODUCTION

In recent years, polarization reconfigurable antennas have received much attention due to their attractive advantages, such as avoiding the detrimental fading loss caused by multipath effects and reusing the frequency spectrum to increase the channel capacity. Corresponding to this trend, many efforts have been made on the exploration of polarization reconfigurable microstrip antennas which could switch their polarization characteristics in real time [1].

Most of the polarization reconfigurable microstrip antennas are realized by integrating PIN diodes [2]–[6], microelectromechanical systems (MEMS) switches [7], [8], or varactor diodes [9] into the radiating elements. Nevertheless, the necessary biasing circuits of the designs could adversely affect the radiation performance of the antennas. On the other hand, integrating RF switches into the feed structures instead of the radiating structures may go far towards settling this problem [10]–[14]. In [10], a polarization reconfigurable patch antenna was proposed to switch between the left-hand circular polarization (LHCP) and right-hand circular polarization (RHCP). The function was realized by electrically controlling two inserted PIN diodes between the rhombus-shaped patch and the Y-shaped feed line. In [11] and [12], two slot antennas with switchable vertical and horizontal polarizations for the WLAN application, realized by a switchable feed structure controlled by PIN diodes, were proposed. However, these designs could merely implement two switchable polarization states. In [13] and [14], two reconfigurable patch antennas with a quadri-polarization diversity via integrating PIN diodes into feed networks were reported. However, both designs could only achieve two orthogonal linear polarization directions [13], [14], which can hardly meet the requirements of future wireless communications.

In this paper, a novel polarization reconfigurable patch antenna integrated with a switchable feed network is presented. By changing the operating state of four pairs of PIN diodes in the switchable feed network, the feed point of the circular patch antenna can be switched. Correspondingly, four different linear polarization states can be produced with the direction along 22.5°, 67.5°, 112.5°, and 157.5° referring to x-axis at a 45° interval. Invariable operating frequency and

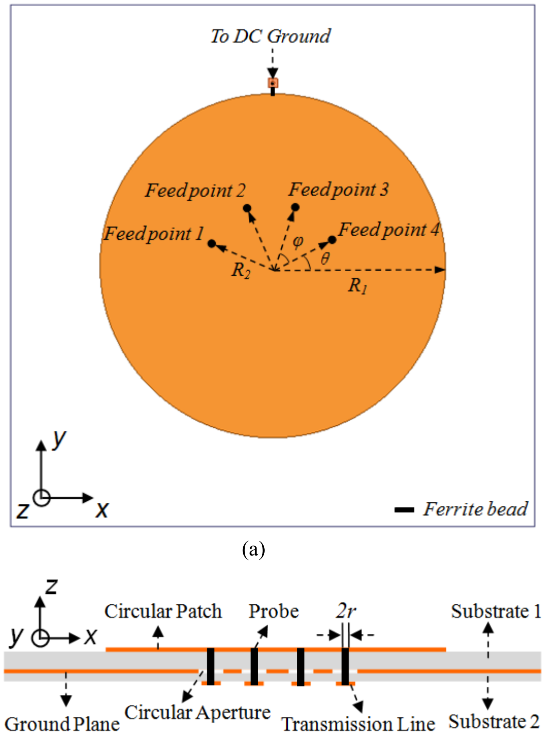

FIGURE 1. Geometry of the proposed antenna: (a) top view; (b) side view. The parameters of the antenna are $R_1 = 28$ mm, $R_2 = 8$ mm, $\varphi = 45°$, $\theta = 22.5°$, $r = 0.4$ mm.

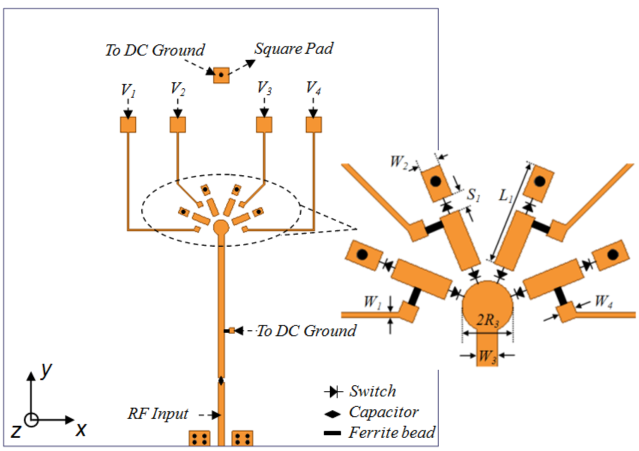

FIGURE 2. Feed network of the proposed antenna. The parameters of the antenna are $W_1 = 0.3$ mm, $W_2 = 1.2$ mm, $W_3 = 1.2$ mm, $W_4 = 1$ mm, $S_1 = 1$ mm, $L_1 = 6.3$ mm.

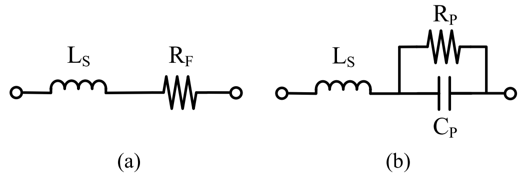

FIGURE 3. Equivalent circuits of the PIN diode: (a) ON state; (b) OFF state.

TABLE 1. Values of elements of the PIN diode.

Element	Value
L_S	0.6 nH
R_F	1.2 Ω
R_P	5 kΩ
C_P	0.15 pF

TABLE 2. Different polarization states of the proposed antenna.

	State 1	State 2	State 3	State 4
V_1/V	1.5	0	0	0
V_2/V	0	1.5	0	0
V_3/V	0	0	1.5	0
V_4/V	0	0	0	1.5
Selected feed point	point 1	point 2	point 3	point 4
Polarization direction	157.5°	112.5°	67.5°	22.5°

excellent radiation performance are achieved for all the different polarization states. In addition, the proposed design can offer more than four reconfigurable linear polarization directions by adding more switchable paths in the feed network. Details of the antenna design are described, and both simulated and experimental results are presented.

II. ANTENNA STRUCTURE AND ANALYSIS

Fig. 1 depicts the structure of the proposed antenna. The antenna consists of two stacking substrates: Substrate 1 with a radiating patch and Substrate 2 with a switchable feed network. A circular radiating patch with a radius of 28 mm is etched on the top of Substrate 1 (thickness = 3.175 mm, $\varepsilon_r = 2.2$). Four probes with a radius of 0.4 mm are located 8 mm away from the center of the circular patch. These probes are connected to the feed network that are printed on the bottom of Substrate 2 (thickness = 0.508 mm, $\varepsilon_r = 3.38$). Four circular apertures with a radius of 0.8 mm are etched on the square ground plane (with the size of 100 mm × 100 mm) for the probes to go through. As described in Fig. 2, the feed network consists of an input feed line, four microstrip transmission paths, four pairs of switches, and four DC lines. The characteristic impedances of the feed line and transmission paths are 50 Ω. A 100 pF capacitor is inserted in the input feed line to isolate the DC signals while maintaining the continuity of RF signals. It should be mentioned that the length of four transmission paths should be as short as possible, because the four microstrip transmission paths work as loadings for the radiation patch. These undesired loadings can lead to poor cross-polarization performance, no matter the antenna is operated at which polarization state.

As shown in Fig. 1a and Fig. 2, a shorting pin is used to connect the circular patch with a small square pad on the bottom of Substrate 2 for DC biasing. A ferrite bead (Murata, model BLM18G [15]), operating as a RF choke, is inserted between the patch and the square pad. The input feed line is also connected to a square pad via a ferrite bead. Then the cathodes of all the switches can be supplied with a 0 V DC

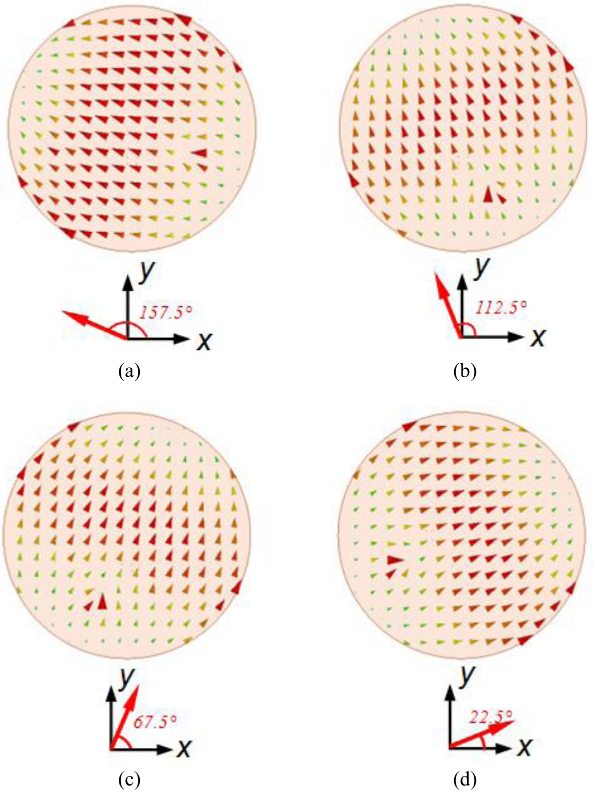

FIGURE 4. Simulated current distributions of the proposed antenna at different polarization states: (a) State 1; (b) State 2; (c) State 3; (d) State 4.

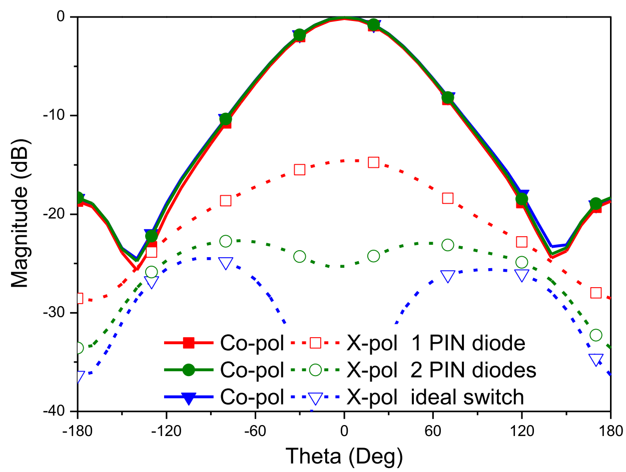

FIGURE 5. Simulated radiation patterns of State 1 with different switches.

voltage by connecting the two square pads to the ground terminal of a DC power supply. On the other hand, four DC lines respectively connect to four transmission paths via four ferrite beads. Then the anodes of the four pairs of switches can be respectively supplied with positive voltages (V_1, V_2, V_3, V_4) by connecting the corresponding DC lines to the positive end of the DC power supply.

The PIN diode is chosen as Infineon BAR50-02V [16]. It can be forward biased to ON state with a DC voltage that supplies 10 mA biasing current and can be in OFF state if left unbiased. The equivalent circuit of the PIN diode is described

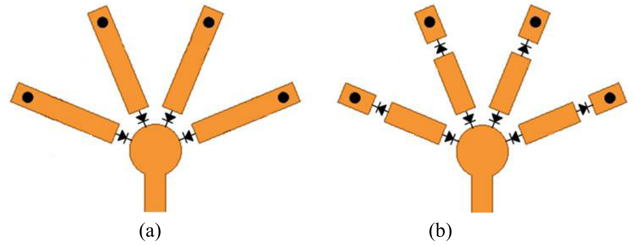

FIGURE 6. Simulated feed network structures with connection of different number of switches: (a) one PIN diode; (b) two PIN diodes in series.

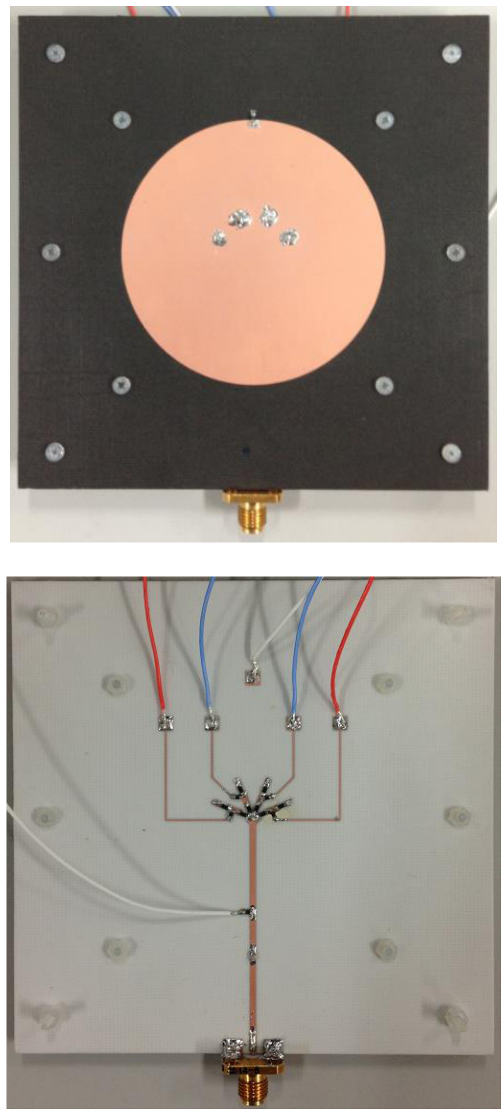

FIGURE 7. Photograph of the fabricated antenna.

in Fig. 3, and the values of the elements at the chosen biasing condition are given in Table 1 [16]. The feed point of the proposed antenna can be selected by setting one pair of switches ON while keeping the other three pairs OFF. Accordingly, the polarization direction of the proposed antenna can be chosen. The four polarization states with respect to different voltage values are summarized in Table 2. Fig. 4 describes the surface current distributions, where we

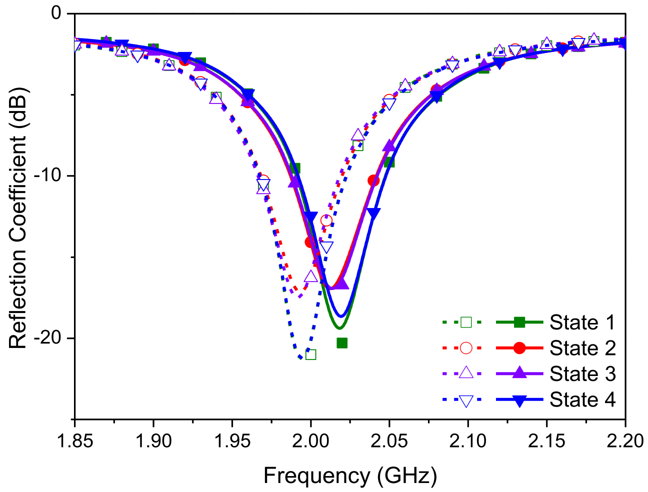

FIGURE 8. **Comparison between the simulated (dashed line) and the measured (solid line) reflection coefficients of the proposed antenna.**

TABLE 3. **Simulated and measured center frequencies, efficiencies and gains at different polarization states of the proposed antenna.**

	State 1	State 2	State 3	State 4
Simulated Center Operating Frequency/GHz	2	1.99	1.99	2
Measured Center Operating Frequency/GHz	2.02	2.01	2.01	2.02
Bandwidth ($\|S_{11}\|$<-10dB)/%	2.5%	2.5%	2.5%	2.5%
Simulated Efficiency	82%	76%	76%	82%
Measured Efficiency	79%	74%	74%	79%
Simulated Gain/dBi	7.1	6.8	6.8	7.1
Measured Gain/dBi	6.9	6.7	6.7	6.9

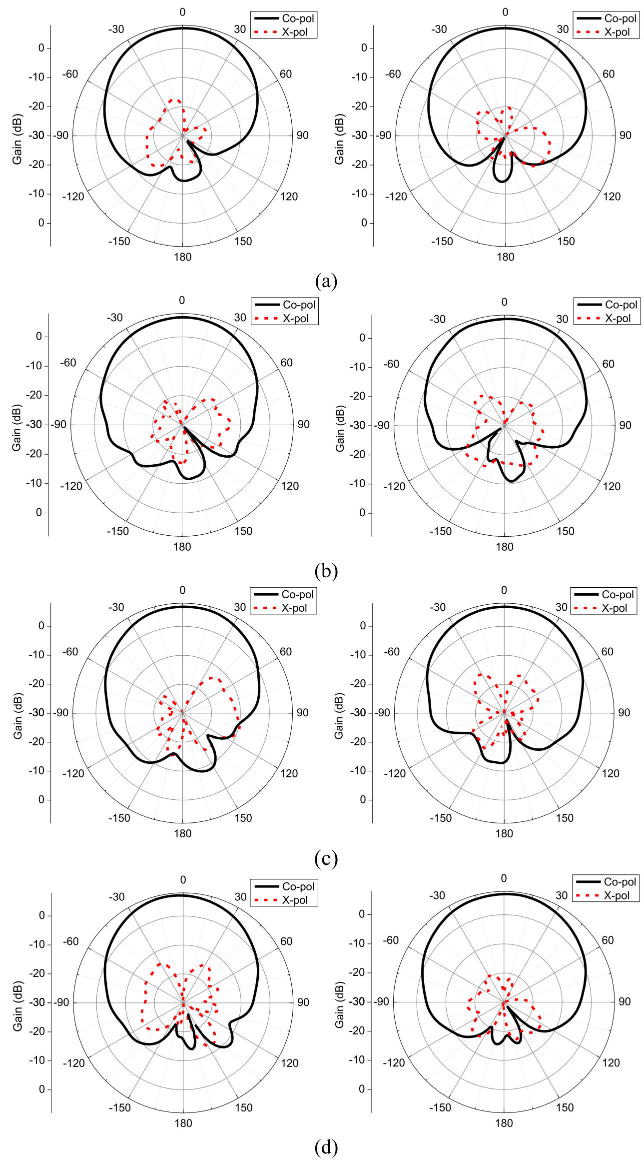

FIGURE 9. **Measured E-plane (left) and H-plane (right) radiation patterns at different polarization states of the proposed antenna: (a) State 1; (b) State 2; (c) State 3; (d) State 4.**

can observe different polarization directions at different states clearly.

It is found that the cross-polarization performance is sensitive to the isolation between the four switchable transmission paths. Fig. 5 shows the simulated radiation patterns of State 1 in three separate cases, namely, one PIN diode as a switch, two PIN diodes in series as a switch, and ideal switch (short circuit for ON state and open circuit for OFF state). Fig. 6 presents the corresponding simulated feed network structures with connection of different numbers of switches. As compared with the one PIN diode case, the two PIN diodes in series can provide the antenna with better cross-polarization performance. Even though more PIN diodes in series can lead to better cross-polarization performance, more PIN diodes will result in larger power losses (insertion losses) and more complicated structure. Therefore, two PIN diodes in series are used in our design. To be mentioned, switches with a higher quality factor, such as MEMS switches, can also realize a better isolation and therefore better cross-polarization performance.

III. SIMULATED AND MEASURED RESULTS

In order to verify the proposed design, a prototype was designed, fabricated and measured. The photograph of the fabricated antenna is depicted in Fig. 7. Ten plastic screws surrounding the circular patch were used to hold the two stacking substrates firmly. The simulation was accomplished using the EM simulation software ANSYS HFSS. Measured results were obtained by an Agilent N5244A network analyzer and a Satimo Starlab near-field measurement system.

Fig. 8 shows the simulated and measured reflection coefficients of the constructed prototype at different polarization states. The measured results indicate that the center

TABLE 4. Comparison between proposed and reported polarization reconfigurable antennas.

Ref.	Antenna Type	Overlapped BW %	Max. Gain (dBi)	Radiation Efficiency %	No. of Diodes	No. of Polarization States	Cross-polarization Level (dB)
[10]	Rhombus-shaped Patch	2%	3.17	n. a.	2	2	n. a.
[12]	Rectangular Ring Slot	21%	3	n. a.	2	2	-9
[13]	Aperture-coupled Patch	3.7%	5	n. a.	8	4	n. a.
[14]	Stacked Ring Patch	3.3%	4.5	45%	6	4	n. a.
This Work	Circular patch	2.5%	6.9	79%	8	4	-25

operating frequency for all the different states are 2.02 GHz with $S_{11} < -18$ dB. It should be mentioned that the slight frequency shift between simulation and measurement is mainly attributed to the parasitic effects of packaged diodes, manufacturing and measuring tolerances.

The simulated and measured efficiencies and gains at different polarization states are presented in Table 3. The simulated efficiencies are larger than 82% and the simulated broadside gains are always larger than 7.1 dBi at different polarization states. The measured efficiencies are larger than 74% and the measured broadside gains are always larger than 6.7 dBi at different polarization states. The slight difference of the efficiency and gain between states 1, 4 and states 2, 3 is attributed to the parasitic effects of the four probes. The slight difference between simulation and measurement is attributed to the parasitic effects of packaged diodes, manufacturing and measuring tolerances.

The radiation patterns of the fabricated prototype were also measured, which are stable for different states. Fig. 9 describes the typical results at 2.02 GHz in the E-plane (left) and H-plane (right) at different polarization states. Apparently, similar broadside radiation is achieved at different polarization states with the cross-polarization levels lower than −25 dB.

IV. COMPARISON AND DISCUSSION

The performance of some reported polarization reconfigurable antennas is summarized in Table 4 to compare with results of this design.

In terms of the gain and radiation pattern, the designs based on conventional patch and slot antennas have the disadvantages of low gains and high cross-polarization levels. Most designs [10], [12], and [14] can only achieve gains of lower than 4.5 dBi. The design in [13] can obtain a maximum gain of 5 dBi but suffer from asymmetric radiation patterns and a dual-port feed structure. In this design, a stable gain of 6.9 dBi and well-controlled radiation patterns are achieved for all the reconfigurable states.

Radiation efficiency is key performance for reconfigurable antennas. The introduced switches or other tuning mechanisms in the reconfigurable designs produce additional power loss. However, the values of the radiation efficiencies are not provided in most of the published designs. A radiation efficiency of smaller than 45% is realized in [14]. On the other hand, a larger than 79% efficiency is achieved in this design, which is comparable with conventional patch antennas.

V. CONCLUSION

In this paper, a novel polarization reconfigurable circular patch antenna is proposed. By changing the operating state of four pairs of PIN diodes, the antenna can realize reconfigurable quadri-polarization diversity features. Furthermore, the operating frequency is maintained at different polarization states with excellent radiation performance. To be mentioned, the proposed design can offer more reconfigurable linear polarization directions by adding more switchable paths in the feed network. With all these attractive properties, the proposed antenna is very attractive for wireless communications.

VI. ACKNOWLEDGMENT

Hui Gu was with the Ministerial Key Laboratory of JGMT, Nanjing University of Science and Technology, Nanjing 210094, China.

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HUI GU was born in Jiangsu, China. He received the M.S. degree in communication and information system from the Nanjing University of Science and Technology, Nanjing, China, in 2016. He is currently with the FN Design & Development Department, ZTE Corporation, Nanjing. His recent research interest focuses on wideband antennas, patch antennas, base station antennas, reconfigurable antennas, and antennas for cognitive radio.

JIANPENG WANG received the Ph.D. degree from the University of Electronic Science and Technology of China, Chengdu, China, in 2007. From 2005 to 2006, he was a Research Assistant with the Institute for Infocomm Research, Singapore. From 2010 to 2011, he was a Research Fellow with the School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. In 2013, he was a Visiting Scholar with the School of Engineering and Physical Sciences, Heriot Watt University, Edinburgh, U.K. In 2014 and since 2016, he has been a Research Fellow with the Faculty of Science and Technology, University of Macau, Macau, China. He is currently an Associate Professor with the School of Electronic and Optical Engineering, Nanjing University of Science and Technology, Nanjing, China. He has authored or co-authored over 60 papers in international journals and conference proceedings. His research interests include microwave circuits, antennas, and low-temperature co-fired ceramic-based millimeter-wave circuits. He is an Associate Editor of the *IET Electronics Letters* (2015-present).

LEI GE (S'11–M'15) was born in Jiangsu, China. He received the B.S. degree in electronic engineering from the Nanjing University of Science and Technology, Nanjing, China, in 2009, and the Ph.D. degree in electronic engineering from the City University of Hong Kong, Hong Kong, in 2015.

From 2010 to 2011, he was a Research Assistant with the City University of Hong Kong. In 2015, he was a Post-Doctoral Research Fellow with the State Key Laboratory of Millimeter Waves, City University of Hong Kong. He is currently an Assistant Professor with Shenzhen University, China. His recent research interest focuses on wideband antennas, patch antennas, base station antennas, reconfigurable antennas, the antennas for cognitive radio, and filtering antennas.

He received the Honorable Mention at the student contest of 2012 IEEE APS-URSI Conference and Exhibition held in Chicago, USA, and the First Prize in the Student Innovation Competition of 2014 IEEE International Workshop on Electromagnetics held in Sapporo, Japan, in 2014.

CHOW-YEN-DESMOND SIM (M'07–SM'13) was born in Singapore in 1971. He received the B.Sc. degree from the Engineering Department, University of Leicester, U.K., in 1998, and the Ph.D. degree from the Radio System Group, Engineering Department, University of Leicester, in 2003. From 2003 to 2007, he was an Assistant Professor with the Department of Computer and Communication Engineering, Chienkuo Technology University, Changhua, Taiwan. In 2007, he joined the Department of Electrical Engineering, Feng Chia University (FCU), Taichung, Taiwan, as an Associate Professor, where he became a Full Professor in 2012. He is currently serving as the Executive Officer of Master's Program with the College of Information and Electrical Engineering (Industrial Research and Development), the Director of Intelligent IoT Industrial Ph.D. Program, and the Director of the Antennas and Microwave Circuits Innovation Research Center with FCU. He has authored or co-authored over 80 SCI papers. His current research interests include antenna design, VHF/UHF tropospheric propagation, and RFID applications. He is a Fellow Member of the Institute of Engineering and Technology, a Senior Member of the IEEE Antennas and Propagation Society, and a Life Member of the IAET. In 2015, he was invited to become the Distinguished Chair Professor (ZhiQian Professor) with the School of Communication and Information Engineering, Shanghai University. He was the TPC Member of the APMC 2012, the APCAP 2015, and the IMWS-Bio 2015. He served as the TPC Sub-Committee Chair (Antenna) of the ISAP 2014. He was a recipient of the IEEE Antennas and Propagation Society Top 10 Outstanding Reviewer Award for Year (2013/2014), (2014/2015), and (2015/2016). He received the Fee Waiver Ph.D. Scholarship from the Radio System Group, Engineering Department, University of Leicester, in 1999. He was invited as the Workshop Speaker in APEMC 2015 and ICAT 2016, and the Invited Speaker of TDAT 2015. He serves as the TPC Chair of the APCAP 2016, and the Chapter Chair of the IEEE AP-Society, Taipei Chapter (from 2016 to 2018).