Received 9 August 2022; revised 27 August 2022; accepted 29 August 2022. Date of publication 6 September 2022; date of current version 19 September 2022.
Digital Object Identifier 10.1109/OJAP.2022.3204926

A Compact 4×4 Filtering Microstrip Patch Antenna Array With Dolph-Chebyshev Power Distribution

WEI NIE [1,2], HUAI-ZHI WEN [1], KAI-DA XU [3,4,5] (Senior Member, IEEE), YU-QUAN LUO [6], XIAO-LONG YANG [1] (Member, IEEE), AND MU ZHOU [1] (Senior Member, IEEE)

[1] School of Communication and Information Engineering, Chongqing University of Posts and Telecommunications, Chongqing 400065, China

[2] Chongqing Key Laboratory of Mobile Communications Technology, Engineering Research Center of Mobile Communications, Chongqing University of Posts and Telecommunications, Chongqing 400065, China

[3] School of Information and Communications Engineering, Xi'an Jiaotong University, Xi'an 710049, China

[4] State Key Laboratory for Manufacturing Systems Engineering, Xi'an Jiaotong University, Xi'an 710049, China

[5] State Key Laboratory of Precision Spectroscopy, East China Normal University, Shanghai 200241, China

[6] State Grid Sichuan Electric Power Corporation Leshan Electric Power Supply Company, Leshan 614000, China

CORRESPONDING AUTHOR: K.-D. XU (e-mail: kaidaxu@ieee.org)

This work was supported in part by the Science and Technology Research Program of Chongqing Municipal Education Commission under Grant KJQN202000630; in part by the Chongqing Natural Science Foundation Project under Grant cstc2019jcyj-msxmX0742; in part by the State Key Laboratory of Advanced Optical Communication Systems Networks under Grant 2022GZKF020; and in part by the State Key Laboratory of Precision Spectroscopy Open Research Program.

ABSTRACT This paper proposes a compact 4 × 4 filtering microstrip patch antenna array with Dolph-Chebyshev distribution implemented by multilayer structure. The proposed antenna array features good filtering performance but contains no extra filtering parts in the feeding or the radiating element. The whole antenna array consists of four 1 × 4 antenna subarrays, each subarray is composed of four patch antennas which are coupled-fed by a single microstrip line. Inside the desired passband, by properly choosing the coupling area along the microstrip line, the patches are induced in-phase currents therefore achieving the excellent radiation characteristics. On the other hand, the four patches can't be properly excited outside the passband which would enable radiation suppression performance. In order to implement a 4×4 filtering microstrip patch antenna array with low sidelobe level (SLL), four subarrays are combined and fed by Dolphy-Chebyshev excitation method. Finally, the proposed antenna array is implemented, fabricated and measured. The maximum measured gain in the passband is 14.7 dBi, and the radiation suppression outside the passband is better than 25 dB.

INDEX TERMS Antenna array, filtering antenna, Dolph-Chebyshev array.

I. INTRODUCTION

WITH the development of wireless communication technology, the RF front ends are required to be miniaturized and multifunctional. Filters and antennas are the critical components in the RF front end and take large circuit area. In recent years, research efforts have been put on the co-design of the filter and antenna to meet the above requirements. In summary, there have been two main approaches to realize the co-design of the filter and antenna. The first way is to embed the filtering characteristic into the feed structure of the antenna [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], such as connecting the filter directly with the antenna which would produce large interconnection loss and take large volume [1], [2]. In [3], [4], [5], [6], the antenna is considered as the last stage or the load of the filter. Capacitively loaded loop based filter [3] and multimode resonators [4] could be integrated with an antenna. A duplexer [5] and the stub-loaded resonators [6] are connected to the patch antenna to realize the filtering characteristic. In addition, power divider and baluns [7], stepped impedance resonators [8] and coupling elements [9] can also be utilized for the integration with the antenna. In [10], high quality factor filters are

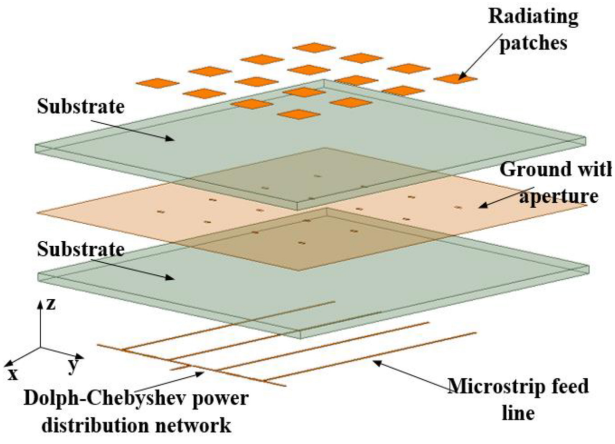


FIGURE 1. The configuration of the proposed 4×4 filtering microstrip patch antenna array.

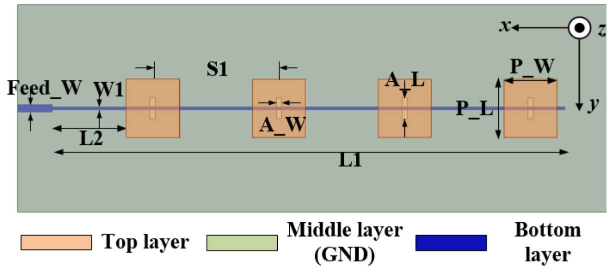


FIGURE 2. The layout of the 1×4 filtering microstrip patch antenna subarray.

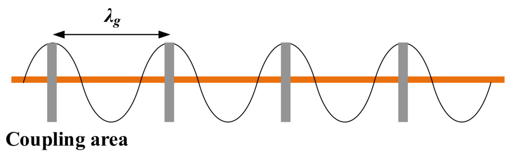


FIGURE 3. The current distribution along the transmission line.

vertically integrated with slot antennas. The second way is to implement the filtering antenna without additional filtering circuits [11], [12], [13], [14], [15], [16], [17], [18], [19], [20]. Shorting pins [11], driven patch and stacked patch [12], [13], [14], metasurface [15] are utilized to realize filtering antenna. In addition, parasitic loops [16], baluns and reflectors [17] are used to implement the filtering antenna. In [18], a broadband patch antenna with high selectivity is obtained by studying the electric and magnetic coupling between the main patch and the parasitic patches. Without complex structure, filtering response is realized by carefully selecting the coupling region between the antenna and the feed line [19]. In [20], radiation null is introduced by placing four parasitic strips close to the main patch antenna.

In this paper, a 4 × 4 filtering microstrip patch antenna array with low sidelobe level (SLL) is presented. Firstly, a 1 × 4 patch antenna subarray is studied to show the effectiveness of the proposed method. The subarray is composed of four microstrip patch antennas and a microstrip feed line which are located at different layer of the substrates. The patches are series fed by the microstrip line through the aperture on the ground layer. By choosing specific coupling area, the patches would be excited with in-phase currents at the desired frequency. On the other hand, the patch antennas can't be excited properly outside the operating frequency band therefore radiation suppression is realized. Furthermore, four subarrays are combined and fed by a Dolph-Chebyshev network to implement a high gain filtering microstrip patch antenna array with low SLL. Finally, the proposed antenna array is fabricated for measurement, the measurement results verify the design.

II. FILTERING MICROSTRIP PATCH ANTENNA ARRAY

A. ANTENNA ARRAY CONFIGURATION

Fig. 1 shows the configuration of the 4 × 4 filtering microstrip patch antenna array. The whole array consists of the same four 1 × 4 subarrays based on three metal layer structure bonded by two substrates. The substrate used in this paper is Taconic RF-35 with thickness of 0.508 mm and relative permittivity of 3.5. Each subarray is composed of a microstrip feed line and four patch antennas. The feed line and the patch antennas are placed at the top and bottom layer, respectively. The patches are series fed by the feed line though the aperture on the middle layer of the substrate which functions as the ground. The Dolph-Chebyshev power distribution network is utilized to feed the four subarrays to form a 4 × 4 microstrip patch antenna array. Fig. 2 depicts the layout of the 1 × 4 filtering microstrip patch antenna subarray, its working mechanism would be studied and investigated first.

B. FILTERING ANTENNA ARRAY WORKING MECHANISM

According to the transmission line theory, the currents along a transmission line is periodically distributed in the sinusoidal form as shown in Fig. 3. The period is λ_g, where λ_g is the guided wavelength at working frequency f_0. The areas with the same current magnitudes and phases are λ_g away from each other. Then if the areas with the maximum current distribution (denoted by the grey area in Fig. 3) are chosen along the transmission line to be coupled to the patch antenna, it is expected that the excited currents on the patch antenna have the same phase as along as these adjacent coupling areas are strictly λ_g away from each other (the center to center distance of the adjacent patch antenna is λ_g). Consequently, the patch antennas coupled-fed by the feed line would radiate in the same direction which would produce high radiation performance inside the working frequency band.

However, the distance between the adjacent coupling area is no longer λ_g outside the working frequency band which means the currents in these areas are not in phase any more. Therefore, the currents excited on the patch antenna in this case would not have the same phase either. Then radiation performance would be degraded or the radiation null would be generated when the radiation fields of

TABLE 1. Physical dimensions in Figure 2. (Units:mm).

Feed_W	W1	L1	L2	S1	A_W	A_L	P_L	P_W
1.12	0.3	147.4	21.43	36.2	0.7	4	17	15.15

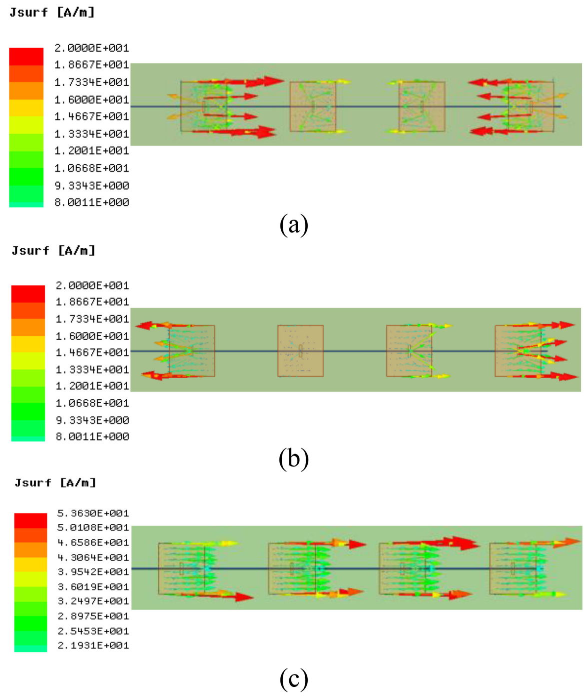


FIGURE 4. The current distribution on the patch antennas at (a) 4.3GHz, (b) 5.7GHz, (c) 5GHz.

each patch antenna are out of phase. Based on the above theory, the radiation inside the working frequency band and radiation suppression outside the working frequency band of the antenna array could be realized just by tricky selection of the coupled feeding area along the transmission line.

Fig. 4 illustrates the excited current distribution on the patch antenna. The patches are λ_g away from the adjacent ones, λ_g is the guided wavelength at 5 GHz. The physical dimensions in Fig. 2 are tabulated in Table 1. Fig. 4 (a) demonstrates the excited currents distributions at 4.3 GHz on the four patches the first two patches present out-of-phase currents compared to the third and fourth ones. The current distribution means the four patches can't radiate collaboratively and suppress each other at the far field. It's the same case in Fig. 4 (b), the current distribution show anti-phase feature at 5.7 GHz. The radiation null would be generated when the exited currents on the patches are out of phase. At 5 GHz, Fig. 4 (c) shows good in-phase current distribution on the four patches, then enhanced radiation is realized at 5 GHz whereas radiation suppression at 4.3 GHz and 5.7 GHz is realized.

Fig. 5 plots the simulated S-parameter and antenna gain of the antenna subarray in Fig. 2. In Fig. 5, the impedance matching bandwidth is 100 MHz ($|S_{11}|<-10$ dB). The maximum gain within the passband is 10.5 dBi, and radiation nulls

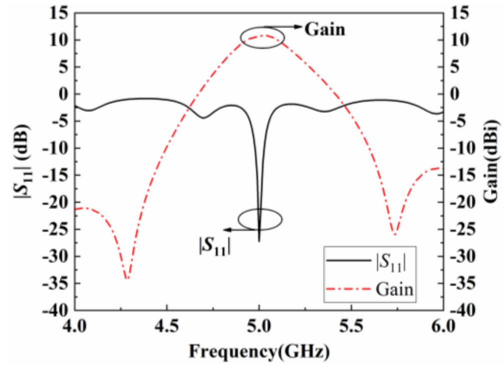


FIGURE 5. The $|S_{11}|$ and gain of the 1×4 filtering microstrip patch antenna subarray.

are generated around 4.3 GHz and 5.7 GHz, respectively. Consequently, good filtering effect is realized.

III. MICROSTRIP ANTENNA ARRAY WITH DOLPH-CHEBYSHEV POWER DISTRIBUTION

The above analysis verifies that filtering characteristics could be obtained by selecting specific coupling area along the transmission line to feed the patch antenna. However, since the power along the transmission line attenuates exponentially so that higher gain could not be realized by just simply adding more radiating elements along the feed line. In this section a Dolph-Chebyshev power distribution network is utilized to feed the previously proposed 1 × 4 filtering microstrip patch antenna subarray. Four subarrays are combined and fed by the Dolph-Chebyshev network so that higher gain and low SLL could be realized.

The schematic of the Dolph-Chebyshev network with 4 uniformly spaced subarrays is presented in Fig. 6. The network provides power distribution which is symmetrical about the center of the array. When SLL of the antenna array is chosen to be −26 dB, the current distribution of the network could be determined as [21]:

$$i_1 : i_2 = 1 : 0.47 \tag{1}$$

For the subarrays on the both sides of the center, the adjacent subarrays are connected by a network which is composed of four $\lambda_g/4$ transmission line with impedance of Z_0, and Z_1, respectively. In order to achieve the amplitude distribution in (1), it is necessary to analyze the relationship between Z_0 and Z_1. The four $\lambda_g/4$ series connected transmission line network could be modeled as shown in Fig. 7, Z_A represents the impedance of each subarray. The relationship between the currents and voltages of the two port of the network could be expressed by the ABCD matrix as:

$$\begin{bmatrix} U_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} \frac{Z_0^2}{Z_1^2} & 0 \\ 0 & \frac{Z_1^2}{Z_0^2} \end{bmatrix} \begin{bmatrix} U_2 \\ I_2 \end{bmatrix} \tag{2}$$

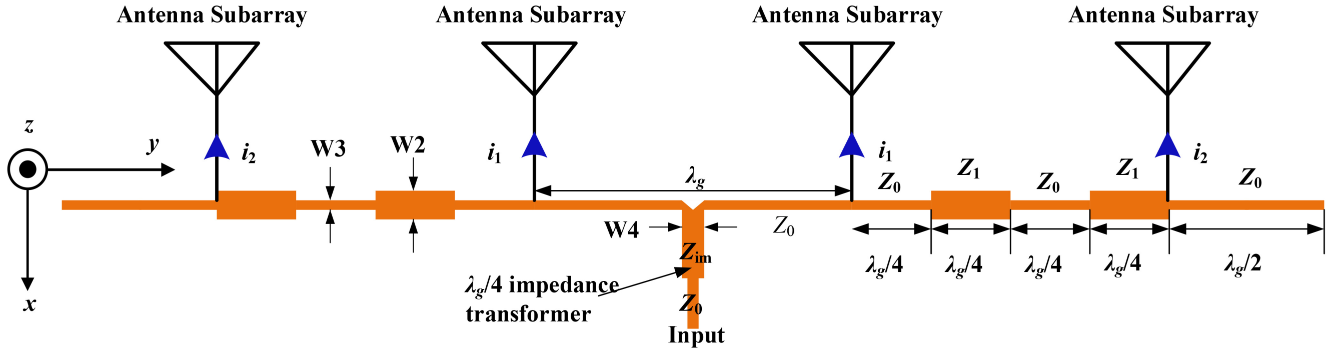


FIGURE 6. The configuration of the Dolph-Chebyshev antenna array.

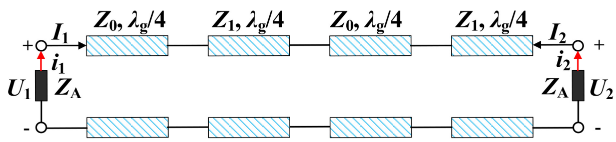


FIGURE 7. The model of the four $\lambda_g/4$ series connected transmission line network.

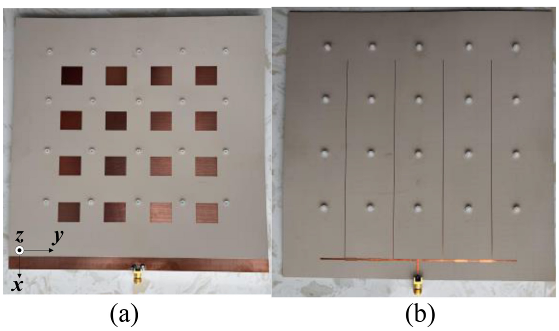


FIGURE 8. The fabricated filtering microstrip patch antenna array. (a) Top view. (b) Bottom view.

Then the currents i_1 and i_2 across the Z_A could be related xzas

$$\frac{i_1}{i_2} = \frac{U_1/Z_A}{U_2/Z_A} = \frac{Z_0^2}{Z_1^2} \tag{3}$$

According to (1), then $Z_1 = 0.6855 \times Z_0 = 34.27\ \Omega$ since $Z_0 = 50\ \Omega$, and the impedance value Z_{im} of the impedance transformer in Fig. 6 is 35.35 Ω. The physical dimensions in Fig. 6 could be determined as W2 = 1.98 mm, W3 = 1.12 mm, W4 = 1.9 mm.

Based on the above analysis, the design procedure for the proposed filtering antenna array could be explained as: 1) Design the individual radiating patch for the working frequency f_0; 2) Place 4 radiating patches along the feed line with center to center intervals of λ_g to form the 1 × 4 filtering microstrip patch antenna subarray. The coupling between the feed line and the patches could be tuned by adjusting the aperture dimensions; 3) Design the Dolph-Chebyshev power distribution network following the equation (1)-(3); 4) Combine the 1 × 4 subarray by the Dolph-Chebyshev network to obtain the 4 × 4 filtering antenna array.

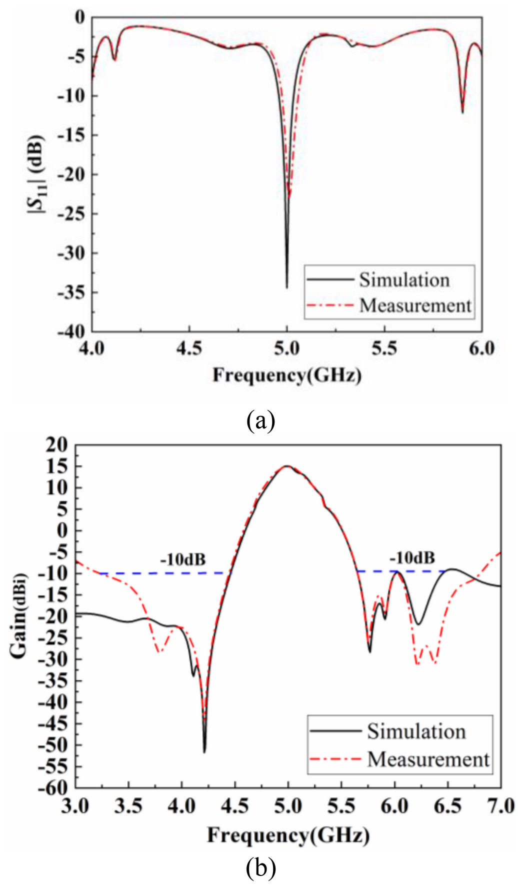
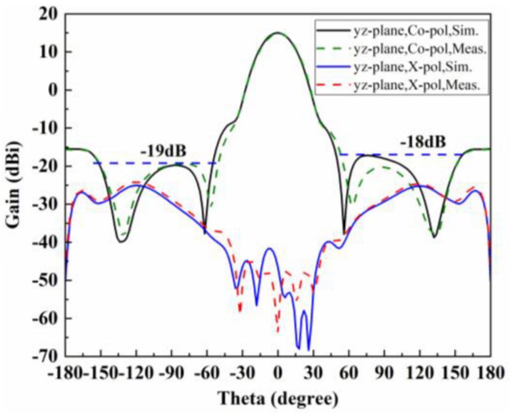


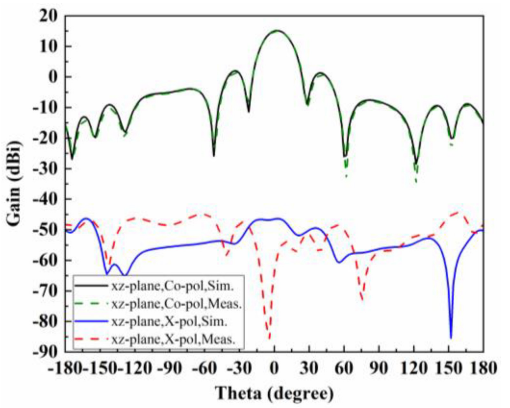
FIGURE 9. Simulation and measurement comparison of the proposed filtering antenna array. (a) $|S_{11}|$. (b) Gain.

IV. IMPLEMENTATION AND MEASUREMENT

To verify the feasibility of the design approach proposed above, a filtering microstrip patch antenna array with Dolph-Chebyshev power distribution is implemented and fabricated with a three metal layer structure bonded by two substrates as shown in Fig. 1. The fabricated antenna array is shown in Fig. 8. The comparisons between the simulation and measurement are presented in Fig. 9. In Fig. 9 (a), the measured impedance bandwidth ($|S_{11}| < -10$ dB) is 100 MHz when the center frequency is chosen to be 5 GHz, and the fractional



(a)



(b)

FIGURE 10. The simulated and measured radiation patterns of the proposed antenna array. (a) yz plane. (b) xz plane.

bandwidth is 2%. The proposed antenna array could be applied to the scenario which requires compact RF front-end and narrow bandwidth such as the NB-IoT (Narrow Band Internet of Things). In Fig. 9 (b), the measured maximum gain is 14.7 dBi while the simulated gain is 15.2dBi. The tiny disagreement may be attributed to the fabrication inaccuracy and SMA connector loss. The gain suppression levels at the lower- and upper-stopband are both better than 25 dB which matches the simulation well. Due to the multiple radiation nulls generated at the stopband, excellent roll-off effect is achieved.

At 5 GHz, the co-pol and x-pol realized gain patterns in the xz and yz plane are depicted in Fig. 10 (a) and (b), respectively. In the xz plane, the x-pol level is lower than -45 dB. In the yz plane, the SLL is 25 dB lower than the peak gain in the operating band due to the utilization of the Dolph-Chebyshev power distribution network. Table 2 compares the proposed work with some previous publications.

V. CONCLUSION

In this paper, a 4 × 4 filtering microstrip patch antenna array is proposed. The microstrip feed line, ground metal and the patch antenna are placed at different layers of the substrates. The patch antennas are coupled-fed by the feed line through the aperture of the ground. By choosing the coupling area which can excite in phase currents on the patches inside the working frequency band and out-of-phase currents on the patches outside the passband, then high performance radiation inside the passband and radiation suppression outside the passband is achieved. To further reduce the SLL of the antenna array, a Dolph-Chebyshev power distribution network is utilized to feed the array. The proposed antenna array shows 14.7 dBi measured gain at 5 GHz, radiation suppression level outside the passband is better than 25 dB.

TABLE 2. Comparison between this work and previous publication.

Ref.	Frequency (*GHz*)	Gain (*dBi*)	Stopband suppression level (dB)	SLL suppression
[4]	5.22	10.5	17.5	No
[6]	3.5	10.6	15	Yes
[7]	5	9.6	15	No
[12]	2.5	9.7	21	No
[13]	1.79/2.1	14.6/15.2	13/19	No
This work	5	14.7	25	Yes

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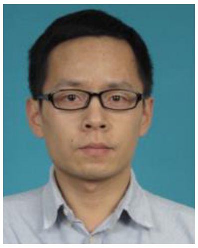
WEI NIE received the Ph.D. degree from the University of Electronic Science and Technology of China, Chengdu, China, in 2015. From July 2015 to July 2016, he worked as an Engineer with Huawei. Since August 2016, he has been working as a Lecturer with the Chongqing University of Posts and Telecommunications, Chongqing, China. His current research area includes microwave and mm-wave passive devices and antenna technology.

HUAI-ZHI WEN received the B.Sc. degree from the Hunan University of Technology, Zhuzhou, China, in 2020. He is currently pursuing the master's degree with the Chongqing University of Posts and Telecommunications, Chongqing, China. His main research interest includes indoor positioning and visual slam.



KAI-DA XU (Senior Member, IEEE) received the B.E. and Ph.D. degrees in electromagnetic field and microwave technology from the University of Electronic Science and Technology of China (UESTC), Chengdu, China, in 2009 and 2015, respectively.

From 2012 to 2014, he was a Visiting Researcher with the Department of Electrical and Computer Engineering, Duke University, Durham, NC, USA, under the financial support from the China Scholarship Council. In 2015, he joined the Department of Electronic Science, Xiamen University, Xiamen, China, as an Assistant Professor. From 2016 to 2017, he was a Postdoctoral Fellow with the State Key Laboratory of Millimeter Waves, City University of Hong Kong, Hong Kong. From 2018 to 2019, he was an Honorary Fellow with the Department of Electrical and Computer Engineering, University of Wisconsin–Madison, Madison, WI, USA. Also, he was awarded a Fellowship from the Japan Society for the Promotion of Science (JSPS) and was the JSPS Fellow with the Department of Communications Engineering, Graduate School of Engineering, Tohoku University from November 2019 to May 2021. He was successfully selected into the "Youth Talent Support Program" of Xi'an Jiaotong University (XJTU) in May 2019, and joined the School of Information and Communications Engineering in XJTU in January 2020. He has authored and coauthored over 140 papers in peer-reviewed journals and over 50 papers in conference proceedings. His current research interests include RF/microwave, mm-wave/THz devices and antenna arrays.

Dr. Xu was a recipient of the National Graduate Student Scholarship in 2012, 2013, and 2014 from the Ministry of Education, China. He received the UESTC Outstanding Graduate Awards in 2009 and 2015. Since 2017, he has been served as an Associate Editor for both the IEEE ACCESS and *Electronics Letters*. He has also served as an Editorial Board Member for both the *AEÜ-International Journal of Electronics and Communications* and *MDPI Electronics*.

YU-QUAN LUO received the bachelor's degree from Chongqing University, Chongqing, China, in 2014. From July 2014, he worked as an Electrical Engineer with State Grid Sichuan Electric Power Corporation Leshan Electric Power Supply Company, Leshan, China. His current research area includes communication technology in electrical grid.

XIAO-LONG YANG (Member, IEEE) was born in 1987. He received the M.Sc. and Ph.D. degrees in communication engineering from the Harbin Institute of Technology in 2012 and 2017, respectively. From 2015 to 2016, he was a Visiting Scholar with Nanyang Technological University, Singapore. He is currently a Lecturer with the Chongqing University of Posts and Telecommunications. His current research interests include cognitive radio networks, energy efficiency optimization, and manifold learning.

MU ZHOU (Senior Member, IEEE) received the B.S., M.S., and Ph.D. degrees in the information and communication engineering from the Harbin Institute of Technology, Harbin, China, in 2006, 2008, and 2012, respectively. He was a joint-cultivated Ph.D. student with the University of Pittsburgh, USA, and a Postdoctoral Research Fellow with the Hong Kong University of Science and Technology, China. Afterward, he joined Chongqing University of Posts and Telecommunications (CQUPT), Chongqing, China, where he has been a Full Professor since 2014. He is currently the Associate Dean of Graduate School of CQUPT and the Vice Director of Mobile Communications Engineering Research Center of Ministry of Education. His research interests include wireless localization and sensing, quantum radar, multisource information fusion, and machine learning. He serves as an Early Career Advisory Board Member for IEEE/CAA JOURNAL OF AUTOMATICA SINICA.