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Development of Low-Profile Filtering Antennas With Dual-Mode Cavities

ZHAN WANG (Student Member, IEEE), AND YUANDAN DONG (Senior Member, IEEE)
School of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China
CORRESPONDING AUTHOR: Y. DONG (e-mail: ydong@uestc.edu.cn)

ABSTRACT Two filtering antennas implemented on the dual-mode cavities are proposed, investigated and experimentally verified in this paper. They are developed based on the single-layer substrate integrated waveguide (SIW) technology. The rectangular SIW dual-mode cavities (using TE_{102}, TE_{201} and TE_{301} modes) are effectively stimulated with a simple capacitive feeding near the diagonal line of the cavity. Surface current distribution is firstly analyzed for the optimal positions of slot radiators. Two rectangular slots are etched on the top surface of the SIW cavity, which are used to interfere the original current flow of one particular mode and generate radiation. These orthogonal dual-modes are used to obtain a filtering response. Their resonance frequencies are close to each other leading to field rotation and interaction with a radiation null generated outside the passband. The radiation and filtering function are achieved simultaneously by the dual-mode cavity, therefore only one cavity is required, resulting in a compact and simple antenna configuration. Good agreement has been observed between the simulation and measurement. They offer a variety of nice features, such as interesting working mechanism, low-profile, high radiation gain and good passband selectivity, which are also suitable for high-frequency antenna application.

INDEX TERMS Dual-mode cavity, dual-mode filter, filtering antenna, planar antennas, slot antennas, substrate integrated waveguide (SIW).

I. INTRODUCTION

ANTENNAS and filters are the key RF/microwave components for the receiver and transmitter subsystems [1]–[6]. Their specifications substantially impact the performance of the radio systems. In conventional wireless architectures, the antenna and filter are implemented separately, they are connected through transmission lines with some additional matching circuits, which suffer from additional loss and a large size. Therefore, filtering antennas, or filtennas, have been widely investigated in recent years [7]–[14], which could significantly minimize the transmission loss and achieve an overall reduced system size.

Several different-type filtering antennas based on substrate integrated waveguide (SIW) technology have been developed and reported in [15]–[19]. For instance, in [13], a millimeter-wave filtering antenna array has been proposed, where patch array is fed by an SIW four-way anti-phase filtering power divider. In [15] and [16], the single and dual-band antennas based on the SIW have been proposed. In fact, both of them can be considered as a combination of a slot SIW antenna and a traditional SIW single or dual-mode filter, which limits the overall size reduction. In [17], a 3-D millimeter-wave filtering antenna is presented, where two-layer SIW are employed. In [18], an SIW filtering antenna with a controllable radiation null was presented, in which the null comes from the split-TE_{101} mode resonators. Recently, a dielectric-resonator-based filtering antenna was reported in [20] with two controllable radiation nulls.

In this paper, two novel and interesting filtering antennas using the dual-mode cavities (TE_{102}/TE_{201} and TE_{102}/TE_{301} dual-modes) are proposed, studied, and experimentally verified, respectively. Two rectangular slots, which could be considered as two magnetic dipoles, are etched on the two edges of the cavity and excited in-phase, which boosts the antenna radiation gain. It is used to form a filtering response with a radiation null (or transmission zero) introduced by cross coupling of the two modes in the boresight direction outside the passband. It is able to improve the antenna filtering performance.

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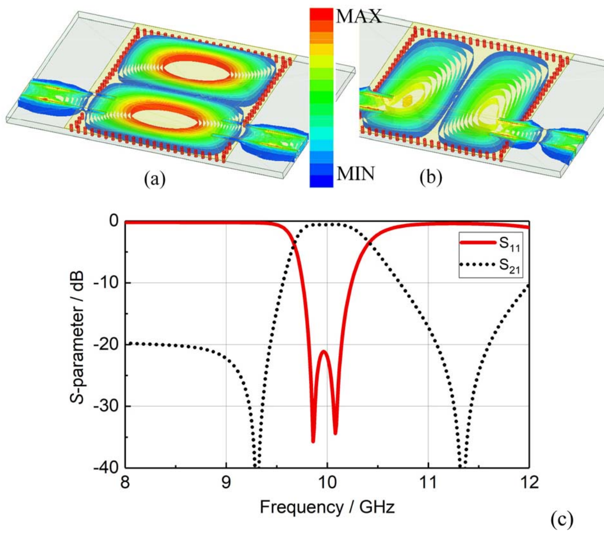

FIGURE 1. Simulated electric field distribution of the (a) TE_{102} and (b) TE_{201} modes inside the dual-mode waveguide filter and (c) its *S*-parameter response.

II. TE_{102}/TE_{201} DUAL-MODE FILTERING ANTENNA

A. DUAL-MODE FILTERING THEORY

Fig. 1 shows a proposed but well known dual-mode SIW filter based on the TE_{102}/TE_{201} orthogonal modes, as well as its simulated electric field (E-field) distribution and *S*-parameters. For a typical SIW dual-mode cavity, the height of substrate is far smaller compared with the wavelength so no modes in vertical direction would be excited at interested frequencies. The resonance frequency of the SIW cavity [14]:

$$f_{m0n} = \frac{c_0}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{leff}\right)^2 + \left(\frac{n}{weff}\right)^2} \tag{1}$$

where, c_0 is the velocity of the electromagnetic wave in free space; ε_r is the relative permittivity of the substrate; l_{eff} and w_{eff} are the equivalent length and width of the SIW cavity, respectively. The TE_{102} and TE_{201} modes are close to each other and orthogonally distributed with a rotating field. In the above dual-mode filter, due to that both of the TE_{102}/TE_{201} mode transmission path and the source-to-load path co-exist in the same cavity, the left and right transmission zeros outside the passband can be obtained by appropriately adjusting the structure and the position of input/output lines.

In our antenna designs, the slots are etched on the top layer of the SIW cavity, which are used to replace the output loading compared with the dual-mode filter. Overall, the cavity incorporated with slots not only generates radiation, but also exhibits a dual-mode filtering character. The position of the slots is selected by analyzing the surface current distribution. Fig. 2 shows the current and E-field distribution for the TE_{102}mode of the dual-mode cavity. By placing two slots at the maximum current position perpendicularly to the current flow direction, the slots could effectively disturb the current flow and generate strong radiation. Note all the slots should be excited in-phase for superposed boresight radiation, otherwise the radiation beam may be tilted or cancelled.

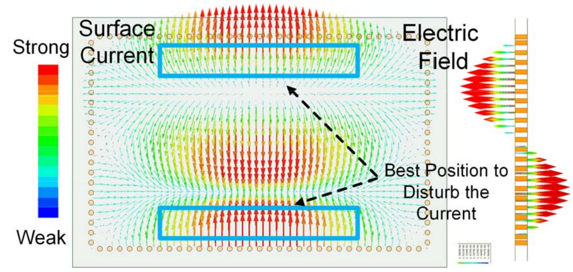

FIGURE 2. Simulated current distribution and electric field variation for the TE_{102}/TE_{201} mode dual-mode cavity.

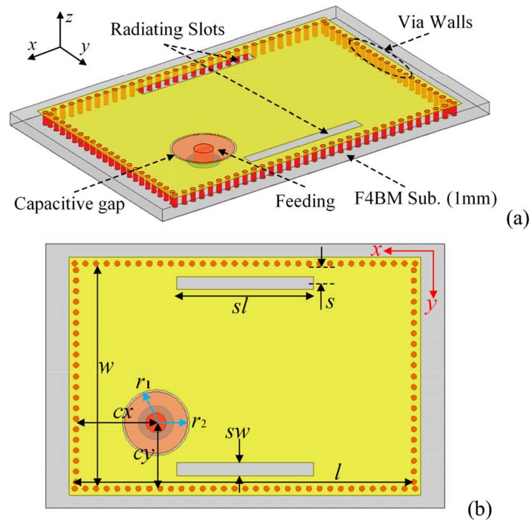

FIGURE 3. (a) 3D view and (b) top view of the dual-mode (TE_{102}/TE_{201} modes) filtering antenna. The size parameters are: $l = 25.6$ mm, $w = 17.2$ mm, $sl = 10.3$ mm, $sw = 1.0$ mm, $s = 1.5$ mm, $cx = 5.85$ mm, $cy = 5.1$ mm, $r_1 = 2.5$ mm, $r_2 = 2.4$ mm.

B. DUAL-MODE FILTERING ANTENNA

Two antennas are proposed and implemented on F4BM220 substrate with thickness is 1.0 mm, a dielectric constant of 2.2, and a measured loss tangent of 0.0009. The metallic vias forming the SIW cavity exhibit a diameter of 0.4 mm and a center-to-center pitch of 0.8 mm. They are simulated and analyzed by ANSYS HFSS, and measured using an R&S ZNB40 vector network and a far-field chamber (700 MHz–40 GHz). In this section, the filtering antenna based on the TE_{102} and TE_{201} mode can be discussed first.

Fig. 3 shows the configuration of the proposed dual-mode SIW filtering antenna. Two rectangular slots are symmetrically etched on the two edges of the SIW cavity. The length of the slots is close to a half of the guided wavelength and the width of the slots has a slight impact on the resonance frequency too. It is noted that due to the slots belong to SIW cavity, so the resonance frequency of the cavity is determined by the cavity and slots. They are used not only to generate radiation, but also be considered as an external output of the filtering antenna. The SMA feeding is placed along on

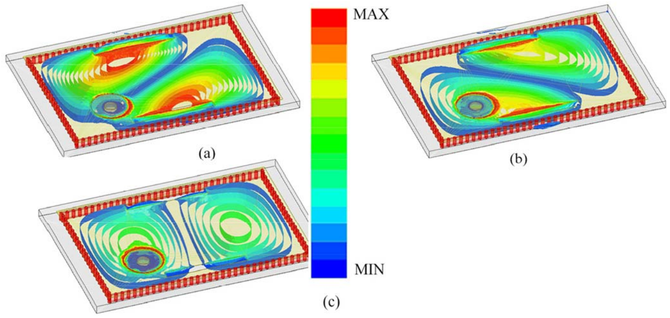

FIGURE 4. Simulated electric field distribution for the dual-mode filtering antenna at (a) 9.93 GHz, (b) 10.02 GHz and (c) 9.76 GHz (radiation null).

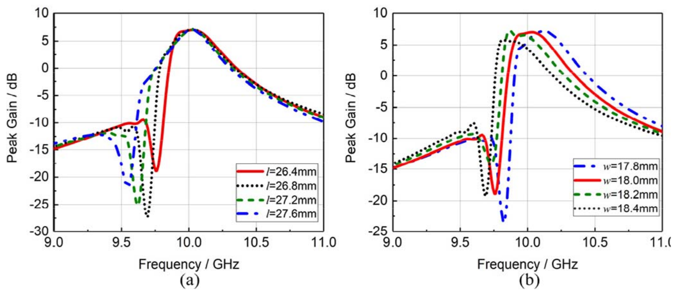

FIGURE 5. A parametric study on the radiation null for the dual-mode filtering antenna: Peak gain by (a) varying the length of the SIW cavity (*l*) and (b) varying the width of the SIW cavity (*w*).

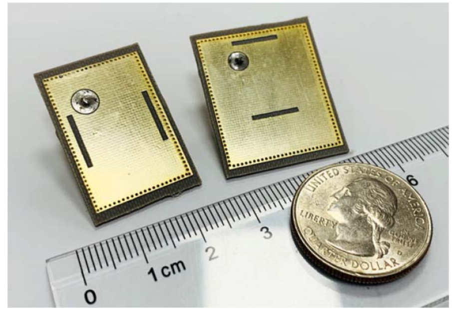

FIGURE 6. A photograph of the fabricated dual-mode (TE_{102}/TE_{201} and TE_{102}/TE_{301} dual-modes) filtering antennas.

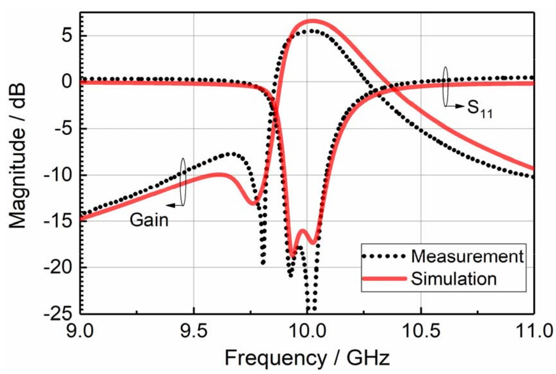

FIGURE 7. The measured and simulated $|S_{11}|$ of the dual-mode (TE_{102}/TE_{201} modes) filtering antenna. Gain is plotted at the broadside direction (+Z) of the antenna.

the diagonal line of the cavity. Its position is selected where the E-field for the two modes are overlapping with similar magnitude, which means that the two modes could be effectively excited simultaneously. The annular gap is etched around the feeding on the top layer, which can be seen as a series slot capacitor to improve the antenna matching.

It is noted that both of the two modes (TE_{102}/TE_{201}) could be clearly observed in the SIW cavity. Their resonance frequencies could be controlled by adjusting the cavity geometrical size and the length of slots. Fig. 4 shows the E-field distribution of the SIW cavity at the frequencies of the two poles and radiation null. It is clearly observed that the two poles come from a pair of split modes from degenerate TE_{102} mode. The two slots hardly cut the current flow of the degenerate TE_{201} mode. Due to the fact that two sides of the same mode are out-of-phase, so the E-field direction of the left slot is opposite to that of the right slot. Thus, a radiation null is achieved in the vertical direction (in z-axis). Note that by tuning the size of cavity, the resonance frequency of TE_{201} mode could shift to higher transition band, so the radiation null could shift to the right side of the passband. Compared with the conventional filtering antenna based on SIW cavity [15]–[17], the proposed dual-mode filtering antenna is implemented on the single-layer SIW and a single cavity without obvious and additional filter structure. They demonstrate a good integration with a compact size of the radiation and filtering functions.

Fig. 5 shows an analysis of the radiation null with different cavity size. When the length of the SIW cavity (l) increases, the l_{eff} is increased, and the resonance frequency of the TE_{201} mode is decreased. Consequently, the radiation null could be moved away from the antenna passband. Meanwhile, two modes are then separated and the passband is affected, so a change in the slope for the left side of the frequency band is observed. When the width of the cavity (w) increases, the w_{eff} is enlarged. Both the TE_{102} and TE_{201} modes are affected, and the position of the passband and radiation null varies.

A photograph of the fabricated dual-mode filtering antenna is shown in Fig. 6. The measured and simulated $|S_{11}|$ and boresight gain response for the TE_{102}/TE_{201} filtering antenna are presented in Fig. 7. Good agreement has been observed. The measured -10 dB bandwidth is 9.89-10.08 GHz (1.9 %). Two transmission poles are observed at 9.93 GHz and 10.02 GHz, and a radiation null can be clearly seen at 9.77 GHz. The out-of-band suppression performance has been improved thanks to the introduction of this radiation null. Note that the Q-factor of the SIW slot antenna is obviously impacted by the thickness of dielectric substrate, so a larger bandwidth can be obtained by using high-thickness substrate.

The measured and simulated radiation patterns at 10 GHz are shown in Fig. 8. The measured and simulated peak gain is 6.15 dBi and 6.65 dBi, respectively, and the cross-pol. component is very low. The slight discrepancies are observed,

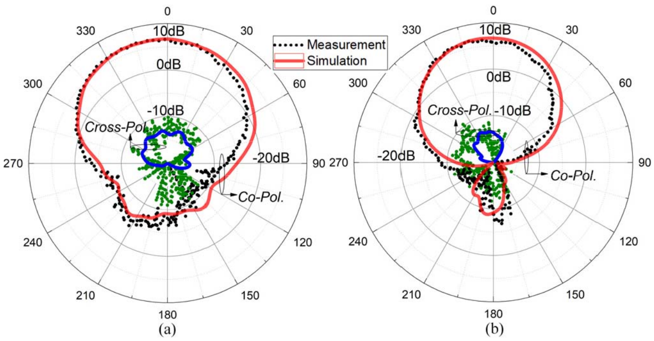

FIGURE 8. The measured and simulated radiation patterns of the dual-mode (TE_{102}/TE_{201} modes) filtering antenna at 10 GHz in (a) phi = 0°, XZ plane and (b) phi = 90°, YZ plane.

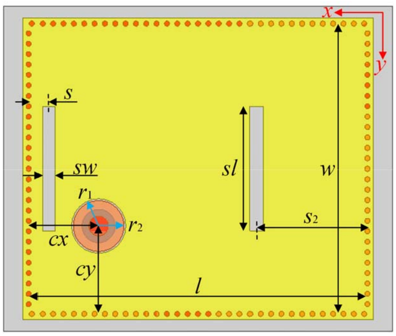

FIGURE 9. Configuration of the TE_{102}/TE_{301} dual-mode filtering antenna. Size parameters are: $l = 26.28$ mm, $w = 22.48$ mm, $sl = 9.55$ mm, $sw = 0.98$ mm, $s = 1.5$ mm, $s_2 = 8.55$ mm, $cx = 5.32$ mm, $cy = 6.75$ mm, $r_1 = 2.1$ mm, $r_2 = 1.96$ mm.

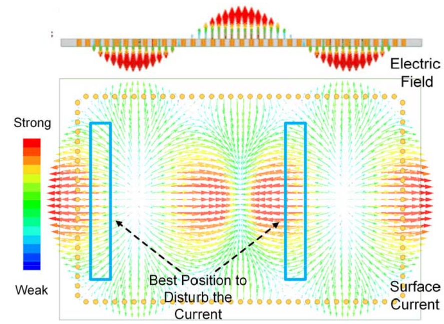

FIGURE 10. Simulated electric field and current distribution for theTE_{301} mode inside the oversized dual mode cavity.

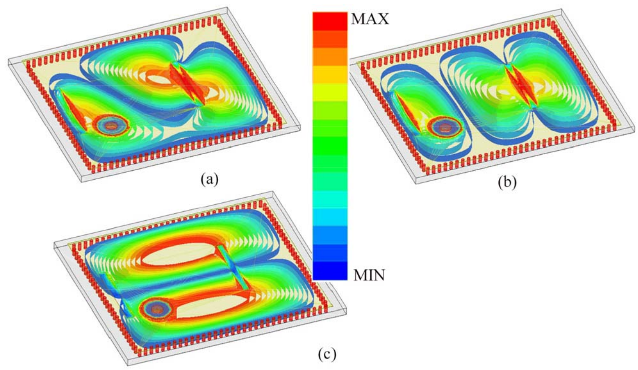

FIGURE 11. Simulated electric field distribution for the dual-mode (TE_{102}/TE_{301} mode) filtering antenna at (a) 9.95 GHz, (b) 10.04 GHz and (c) 9.85 GHz (radiation null).

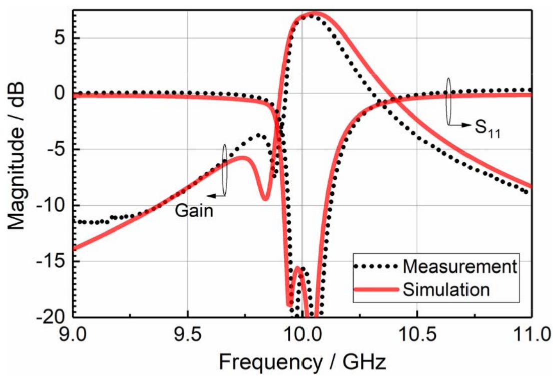

FIGURE 12. The measured and simulated $|S_{11}|$ of the dual-mode (TE_{102}/TE_{301} mode) filtering antenna. Gain is measured at the +Z boresight direction of the antenna.

which are mainly due to the fabrication error and additional loss coming from the SMA connector.

III. TE_{102}/TE_{301} DUAL-MODE FILTERING ANTENNA

TE_{201}/TE_{301} dual-mode cavity have also been used for waveguide dual-mode filter applications [21]. Fig. 9 shows the configuration of the filtering antenna and a photograph of the fabricated antenna is shown in Fig. 6. Two rectangular slots are etched along the y-axis on the top surface of the SIW cavity which are used disturb the current flow for the TE_{301} mode. Fig. 10 shows the current distribution and E-field for the TE_{301} mode. Note that the current flow of the TE_{301} mode could be effectively interfered by the two slot radiators with in-phase excitation. Two slot magnetic dipole radiators could be obtained and moreover, the field of the TE_{102} mode of cavity would be barely affected.

Fig. 11 shows the E-field distribution of the SIW cavity at the frequencies of the two poles and the radiation null. It could be clearly observed that two poles are coming from the degenerate TE_{301} mode, which splits into two slightly different resonances. Due to that two resonance modes are close to each other inside the passband, a rotating dual-mode field distribution can be clearly observed in Fig. 11(a) and (b). For the TE_{102} mode, the slots barely cut the current flow since the slot is oriented in the same direction with the current direction. Besides that, the excited E-field on the left and right sides of the single slot are out-of-phase in Fig. 11(c). Therefore, the radiation from the slots would be cancelled out resulting in a radiation null in the far field outside the radiation passband. It improves the filtering function of the antenna. Similarly, the position of radiation null can be controlled by tuning the dimension of SIW cavity.

The measured and simulated $|S_{11}|$ and gain response are shown in Fig. 12. The measured −10 dB bandwidth is 9.93-10.12 GHz (1.9 %). Meanwhile, a radiation null can be clearly observed at 9.78 GHz and two transmission poles are located at 9.96 GHz and 10.08 GHz, respectively. The measured and simulated radiation patterns at 10 GHz are

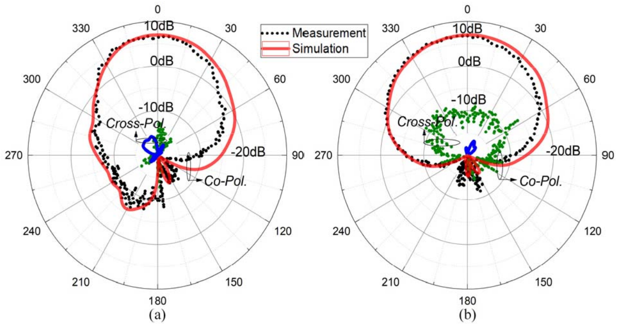

FIGURE 13. **The measured and simulated radiation patterns of the dual-mode (TE_{102}/TE_{301} mode) filtering antenna at 10 GHz in (a) phi = 0°, XZ plane and (b) phi = 90°, YZ plane.**

TABLE 1. **Comparison with other antennas.**

Ref.	Dimension / λ_0^3	Center -Freq. (GHz)	BW / %	Gain / dBi	Technology
[16]	0.71×0.47 ×0.02	5.5	2.6	4.3	dual-cavities (TM_{110}/Half-mode)
[17]	0.60×0.55 ×0.06	31.5	1.56	6.79	dual-layer SIW ($TE_{101}/TE_{102}/TE_{201}$)
[18]	1.2×1.2×0.02	4.5	5.4	6.5	single-cavity (TE_{10}/Half-mode)
Ant.1	0.84×0.57 ×0.03	10.0	1.9	6.15	single-cavity (TE_{102}/TE_{201})
Ant.2	0.87×0.74 ×0.03	10.0	1.9	6.92	single-cavity (TE_{102}/TE_{301})

shown in Fig. 13. The measured and simulated boresight gain is 6.92 dBi and 7.29 dBi, while the cross-pol. component is very low and well suppressed.

IV. COMPARISON WITH OTHER SIW FILTERING ANTENNAS

A performance comparison with other SIW filtering antennas is listed in Table 1. One dual-cavity filtering antenna and one dual-layer SIW filtering antenna were proposed in [16] and [17]. One slotted cavity radiates power while the other is used to achieve filtering, so their structures are complex. Reference [18] proposed a single-cavity filtering antenna using shorting vias based on the TE_{101} mode, but its size is larger.

Relatively, our filtering antennas exhibit a novel structure with a compact size, high gain and good filtering performance for high frequency application.

V. CONCLUSION

Two dual-mode SIW filtering antennas are studied and presented. One mode is used for radiation and the dual-mode is used to realize a radiation null outside the passband by carefully selecting the position of the slots and adjusting the cavity size. They are implemented on the single-layer SIW, with only single cavity and single feeding, showing an very simple and neat antenna configuration. They are exhibiting a low-profile, a compact size, high gain and good filtering performance, which poise them as promising candidates for X-band and above, especially high-frequency directive antenna application.

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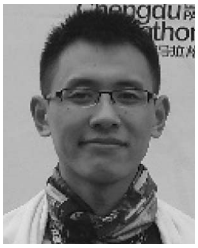

ZHAN WANG (Student Member, IEEE) received the B.S. degree in electrical and information engineering (high-speed rail control) from the Southwest Jiaotong University, Chengdu, China, in 2018. He is currently pursuing the M.S. degree with the University of Electric Science and Technology of China, Chengdu. His research interests include miniaturized antenna and metamaterial application, especially, metamaterial-based antenna.

YUANDAN DONG (Senior Member, IEEE) received the B.S. and M.S. degrees from the Department of Radio Engineering, Southeast University, Nanjing, China, in 2006 and 2008, respectively, and the Ph.D. degree from the Department of Electrical Engineering, University of California at Los Angeles (UCLA) in 2012.

From September 2008 to June 2012, he was a Graduate Student Researcher with the Microwave Electronics Laboratory, UCLA. From September 2012 to February 2016, he was a Senior Engineer with the R&D Hardware Department, Qualcomm, San Diego. From February 2016 to December 2017, he was a Staff Engineer with Universal Electronics, Santa Ana. Since December 2017, he has been a Full Professor with the University of Electronic Science and Technology of China. He has authored over 60 journal and conference papers. His research interests include the characterization and development of RF and microwave components, circuits, antennas, acoustic-wave filters, and metamaterials. He was a recipient of the Best Student Paper Award at the 2010 Asia–Pacific Microwave Conference held in Yokohama, Japan, the Distinguished Expert award presented by Sichuan Province and China Government, and the High Level Innovative and Entrepreneurial Talent award presented by Jiangsu Province. He is serving as a reviewer for several IEEE and IET journals, including the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES and the IEEE TRANSACTION ON ANTENNAS AND PROPAGATION.