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Differential Signal Propagation in Spoof Plasmonic Structure and Its Application in Microwave Filtering Balun

MINGZHU DU, KE CHEN, (Member, IEEE), JUNMING ZHAO, (Member, IEEE), AND YIJUN FENG, (Member, IEEE)
School of Electronic Science and Engineering, Nanjing University, Nanjing 210023, China
Corresponding author: Yijun Feng (yjfeng@nju.edu.cn)

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ABSTRACT In this paper, a filtering balun is proposed based on spoof surface plasmon polariton (SSPP) structure which composes of symmetric H-shaped periodic metallic strip, two types of microstrip-slotline cross-coupling structures and the transition structure between them. The SSPP structure is applied to support odd mode propagation with 180° phase difference and equal magnitude along both sides of the symmetric line, which could transmit the differential signal required for a microwave balun. And then, a new approach for effectively stimulating the odd mode of symmetric H-shaped SSPP structure based on waveguided slotline with a gradient transition structure is proposed and analyzed in detail. In addition, the dispersion characteristic of SSPP can intrinsically bring filtering feature with wide stopband in the balun design. Meanwhile, the two forms of microstrip-slotline cross-coupling structures can not only feed guided wave and realize a pair of balanced ports, but also improve the out-of-band rejection below the objective filtering band. For demonstration, a prototype filtering balun with operating frequency around at 2 GHz is designed, fabricated, and measured. The measured results agree well with the simulated ones which validate the proposed design method and reveal certain advantages of low insertion loss, good amplitude balance and out-of-phase performance as well as the wide stopband.

INDEX TERMS Filtering balun, microstrip to slotline transition, odd mode, spoof surface plasmon polariton (SSPP).

I. INTRODUCTION

Ultra-thin spoof surface plasmon polariton (SSPP) structure as a kind of novel electromagnetic (EM) wave propagation structure in microwave region has attracted much attention since it was first proposed [1]. Comparing with the traditional transmission structures, the SSPP has its unique features. EM wave transmission-line with single metal layer can be realized with sub-wavelength EM field confinements on its surface. Therefore, it can be regarded as one kind of surface wave which is very different from the guided wave on traditional transmission lines [1], [2]. Meanwhile, it can also possess dispersion characteristic with certain cut-off frequency similarly to the natural surface plasmon polariton, which will benefit the frequency band tailoring with a wide stopband. Therefore, various types of SSPP structures and functional devices in microwave components have been developed [3]–[14] including filters [4]–[7], antennas [9]–[11], splitters [12], [13] and so on. Among these studies, the symmetricallymonometallic SSPP structures could support the odd-mode EM wave with equal-amplitude and reverse-phase signal [14]. Such feature is very beneficial for the design of differential signal devices including balun with filtering characteristics. However, few methods have been studied to efficiently excite the odd mode and utilize it for differential signal devices directly.

In addition, with the rapid development of microwave differential circuits in modern communication technology, the filtering balun as a single device which enables the balun with filtering capabilities plays an important role in them.

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It can not only reduce the circuit size, but also convert the unbalanced signals to the balanced ones (vice versa) within a predefined target operating frequency range. Therefore, different methods to achieve filtering balun or to improve its performance have been proposed [15]–[21]. Among the previous designs, the Marchand balun, as well as other improved structures, becomes the most popular method to design the filtering balun [15], [16] because of its easy implementation. Besides, a ring resonator is utilized as an alternative approach to design filtering balun [17]. Moreover, filtering baluns that utilize the microstrip-slotline cross-coupling structure to construct balanced ports with intrinsic 180° phase difference are also proposed in [18], [19]. However, they are mainly based on the use of the traditional microwave transmission structures. Therefore, our primary motivation is to utilize the symmetrically monometallic SSPP to develop a new method for the filtering balun design.

In this paper, a new filtering balun is proposed and extensively studied based on the symmetrically monometallic SSPP structure. On the basis of the preliminary idea introduced in our previous work [22], in-depth analysis together experimental realization and verification are given. Particularly, by utilizing the odd mode propagation supported by the symmetric SSPP structure, equal-magnitude and out-of-phase signals can be easily constructed and efficiently transmitted. Meanwhile, a gradient transition structure is analyzed in detail to realize the effective conversion from guided wave to the odd mode SSPP propagation. In addition, the microstrip-slotline cross-coupling structures are adopted to either feed the guided wave or to further achieve an out-of-phase between the two balanced ports, which can also improve the out-of-band rejection below the target filtering band. It should be remarked that the filtering capability and wide stopband in the balun design can be well controlled by the cut-off dispersion phenomenon of the SSPP. For demonstration and validation, a prototype filtering balun operating around 2 GHz is designed, fabricated and measured. The measured results clearly indicate that the proposed filtering balun could exhibit good performances which verifies the design feasibility.

II. THE UNIT CELL OF SSPP STRUCTURE

The unit cell structure of the proposed symmetric SSPP is an H-shaped structure shown in Fig. 1. It consists of a dielectric substrate with a printed thin metal strip layer where the period, interval, and depth of the proposed structure are indicated with d, a, h, respectively. For exploring the dispersion characteristics of the SSPP unit-cell structure, full-wave EM simulation software CST studio is used to numerically calculate the dispersion relation of the symmetric SSPP structure. The obtained dispersion curves are also plotted in Fig. 1, where $d = 10$ mm and $a = 8$ mm. It concludes that the SSPP mode behaves like a slow-wave with a cut-off property. These are similar to those of an asymmetric SSPPs structure [23]. As presented in [2], when the metal thickness is assumed to be infinite, the dispersion curves for the asymmetric

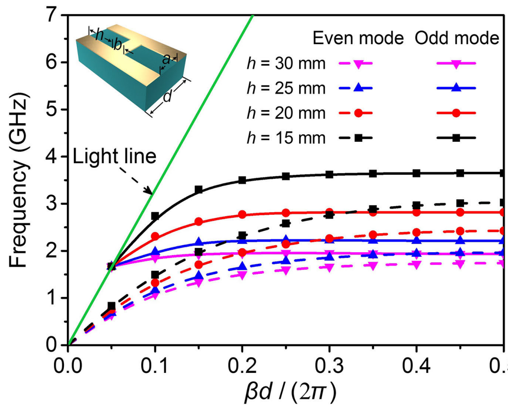

FIGURE 1. The schematic of SSPP unit cell structure and its dispersion curves with different values of *h*.

SSPP modes propagated in the metallic array can be expressed as:

$$\beta = \beta_0\sqrt{1 + (a^2/d^2)\tan^2(\beta_0 h)}, \tag{1}$$

where β indicates the wave number and β_0 represents the propagation constant of EM wave in free space. For SSPP structure, the thickness of metal strip has a limited effect on the modal dispersions [1], and similar to the natural surface plasmon polariton, the SSPP structure also has an asymptote frequency. It is equivalent to the cut-off frequency (f_c) of cavity mode [24], which can be calculated by

$$f_c = c\big/\left(2h\sqrt{\varepsilon_h \mu_h}\right), \tag{2}$$

where c is the light speed in free space, ε_h and μ_h are the relative permittivity and permeability, respectively. Therefore, it can be concluded that the parameter h is one of the dominant influence to the cut-off frequency of the SSPP structure, where an increase/decrease of the parameter h will lead to the decease/increase of the frequency. However, it is different from an asymmetric structure that the symmetric structure can split the SSPP waves propagating along itself into two types of modes: even mode and odd mode [14], as shown in Fig. 1. It can be obtained that for both the even and odd modes, enlarging h will decrease the cut-off frequency, and confine the EM field in the SSPP strip. Therefore, in order to make high-efficiency transmission of SSPPs, a large h should be adopted. Especially, it should be mentioned that the odd mode dispersion supported by the symmetric SSPP structure can effectively construct and transmit an equal-magnitude and out-of-phase signal which is benefit for constructing balun. In addition, the cut-off characteristic can provide a desired frequency filtering capability for the construction of filtering balun.

III. THE EFFICIENT CONVERSION TO THE ODD MODE OF SSPP

In order to take advantages of the SSPP and effectively integrate it with planar circuits, the coplanar waveguide (CPW) [25] or microstrip lines [26] are employed as the major approaches for feeding signals into the SSPP strip and

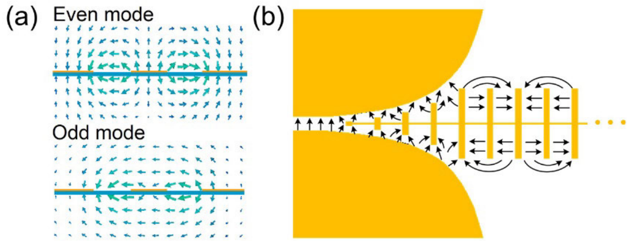

FIGURE 2. **(a) The simulated distributions of *E*-field for the even mode and odd mode in the cross section of CPW, (b) the demonstration to convert the guided waves on slotline to the odd mode of SSPP.**

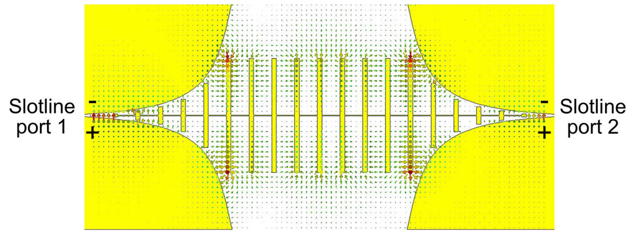

FIGURE 3. **The simulated *E*-field patterns under slotline direct feeding.**

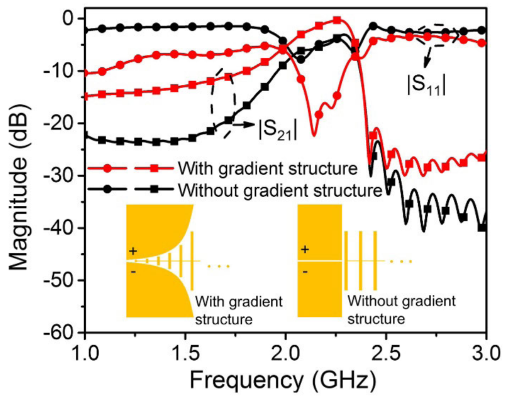

FIGURE 4. **The transmission characteristics of the proposed conversion structure with and without the gradient structures.**

extracting signals directly from it. Especially for the CPW structure, the even and odd modes can be excited as illustrated in Fig. 2(a) according to the transmission line theory of a three-wire system [27]. The desired even mode has ground electrodes at both sides of the center strip, whereas the odd mode has opposite electrode potentials. In most previous researches the even modes of CPW are often utilized for exciting symmetric SSPP [8], [9]. In order to utilize the out-of-phase characteristics in the odd mode of SSPP as discussed above, here we propose to excite the odd mode SSPP based on the odd mode of CPW and apply it to the design of the balun. Fig. 2(b) explicitly shows the conversion from the guided wave on slotline to the odd mode of SSPP. Here, a slotline is employed to excite the odd mode in the CPW [27] and then translate the EM waves through a gradual structure to the SSPP structure. For the slotline part, it can be regarded as a CPW without the center metal strip. As is well-known, the propagation modes on the slotline are quasi transverse electric (TE) modes. The electric field (***E***-field) distribution in the slotline is from one metal side to the other. For the transition part, when the metal strip appears in the center of the slotline, the distribution of the ***E***-field remains basically the same, which can be regarded as the odd mode in the CPW being excited by the slotline. Then, such gradual groove structure can support a mixture of the guided mode and SSPP mode. When the value of h is small, the odd mode of SSPP is still weak and the dominating modes are guided waves. Meanwhile, the ground lines on both sides of CPW are still required to maintain the effective transmission of the guided wave mode. When the value of h becomes larger, the guided waves are gradually converted to SSPPs. In this case, the influence of ground on transmission efficiency becomes weak. Therefore, the ground can be extended outward and terminated along with the gradually enlarged groove length to better achieve all waves transforming to SSPP modes smoothly. On the other hand, as the ground in the transition part is gradually extended outward, the impedance between CPW and plasmonic waveguide will be gradually matched. Accordingly, the simulated ***E***-field patterns in the slotline feeding and transition parts as shown in Fig. 3 verify the validity of the aforementioned conversion process. Meanwhile, the ***E***-field vector lines of the excited mode in the symmetric H-shaped SSPP structure appear to point from one end to the other, which proves that the odd mode in the symmetric H-sharped SSPP is effectively stimulated. In addition, for further demonstrating the effect of gradual coupling structure, the S-parameters of the circuit in Fig. 3 for slotline direct feeding with or without the gradient conversion structure are simulated. After optimization, the optimal solution of the transmission characteristics are obtained. Accordingly, the comparison of the results from the two conversion structures is shown in Fig. 4, which indicates that the transmission characteristics can be much improved with the gradient structure for direct conversion from slotline to SSPP structure. However, due to the weak coupling property in the frequency range below the passband, the deteriorative suppression characteristics in the frequency range below the passband should be improved in the design of balun.

IV. DESIGN OF THE PROPOSED FILTERING BALUN

For making it easier to achieve a desired balun function, two forms of the microstrip-slotline cross transition structures are utilized as feeding ports as illustrated in Fig. 5(a) and (b). The microstrip-slotline cross transition structures used for transmitting EM wave in band-pass filters have been given in [28]–[32]. The microstrip-slotline cross structure at Port 1 is terminated with an open end beyond the slotline portion, while at Port 2 and Port 3 the microstrip-to-slotline cross structure are separated as two identical portions to form the balanced ports. To demonstrate the working mechanism, Fig. 5(c) and (d) depict the ***E***-field distributions in the cross-section view of the two microstrip-to-slotline transition structures, respectively. As expected, it can be obviously observed that an inherent out-of-phase ***E***-field distributions is established on the adjacent grounds of slotline. Therefore, signals

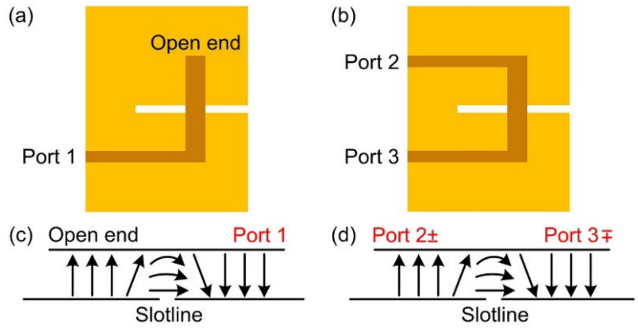

FIGURE 5. The microstrip-slotline cross feeding structures and their cross-section view of *E*-field distributions. (a) and (b) exhibit three ports among which the port 2 and port 3 are balanced pairs. Accordingly, the cross-section view of *E*-field distributions in the microstrip-slotline cross structures are given in (c) and (d) respectively.

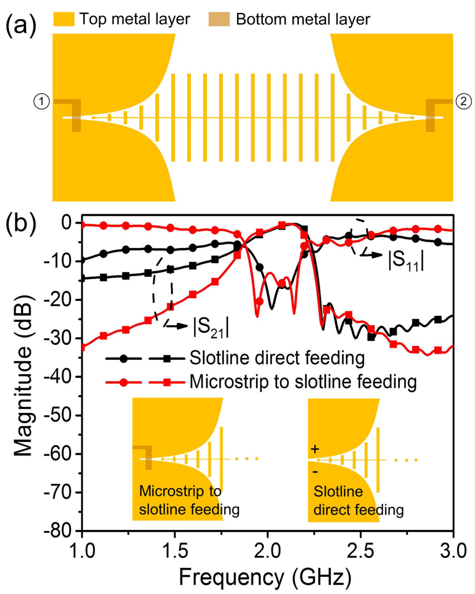

FIGURE 6. (a) The configuration of the transmission structure under cascading two identical micostrip to slotline feeding structures with the SSPP strip, (b) the comparison of the transmission characteristics between the proposed transmission structure and slotline direct feeding.

with 180° phase difference and equal magnitude can be easily obtained at the two balanced ports (Port 2 and Port 3) benefiting the design of the balun.

In order to further verify the effectiveness of the microstrip-slotline cross feeding structure, we test two identical feeding ports connected with the SSPP strip and the conversion parts as shown in Fig. 6(a). Accordingly, the S-parameters of this circuit is calculated and compared with the transmission characteristics of the structure directly fed by slotline shown in Fig. 3, and the results are displayed in Fig. 6(b). It indicates that the pass-band performance could be improved with the microstrip-slotline cross feeding structures. Besides, it should be emphasized that the out-of-band rejection characteristics in the frequency range below the passband becomes better by cascading microstrip-slotline cross feeding structures. In other words, the microstrip-slotline cross feeding structures can greatly improve the frequency selectivity of the circuit. Because, in the frequency range below the passband, the optimized microstrip-slotline feeding structure behaves like a filtering structure and can avoid EM wave converting from microstrip to slotline and thus prevent the weak coupling through using the slotline direct feeding with gradual structure. Therefore, combined with the cut-off frequency characteristic of the SSPP structure, it is expected to achieve the required filtering function in balun design.

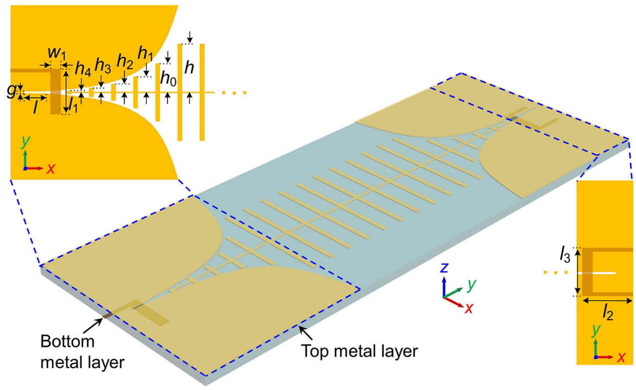

FIGURE 7. The configuration of the proposed filtering balun.

The configuration of the proposed filtering balun has been shown in Fig. 7. Two microstrip-slotline cross feeding structures as shown in Fig. 5(a) and (b) respectively are adopted and integrated into both ends as the input and output. The two ports in Fig. 5(b) act as the balanced ports. Though the parametric study, a passband with expected response can be eventually achieved. Fig. 8(a) shows the z-component of the ***E***-field distribution in the proposed filtering balun at 2 GHz, which clearly indicates that the proposed balun can effectively transmit EM signals from the single-ended port to balanced ports (or vice versa). It is worth mentioning that the value of h clearly affects the cut-off frequency of the unit-cell structure which is illustrated in Fig. 1. Accordingly, the cut-off frequency could be utilized to realize the desired passband as shown in Fig. 8(b). It is obtained that the upside frequency of the passband will decrease by increasing the value of h, exhibiting the controllable bandwidth in the design of such filtering balun. Meanwhile, the cut-off characteristics of the SSPP mode can result in a wide higher stopband.

Based on the above analysis, a filtering balun operating at 2 GHz is designed and implemented on a F4B substrate (thickness is 0.8 mm, dielectric constant is 3.5 and loss tangent is 0.001). From Fig. 1, it can be obtained that the value of h should be chosen as 25 mm to achieve the required passband frequency. After optimizing, the dimensions of the designed filtering balun are set as $l = 6$ mm, $l_1 = 13.3$ mm, $l_2 = 19$ mm, $l_3 = 19$ mm, $g = 0.4$ mm, $h_0 = 14$ mm, $h_1 = 7$ mm, $h_2 = 3.6$ mm, $h_3 = 1.8$ mm, $h_4 = 0.5$ mm, $W_1 = 3.8$ mm and $b = 0.5$ mm. The photographs of the fabricated filtering balun and its simulated and measured results are shown in Fig. 9. It can be obtained that the measured 3-dB fractional bandwidth (FBW) is about 12.5%. The measured insertion loss (IL) and return loss are about

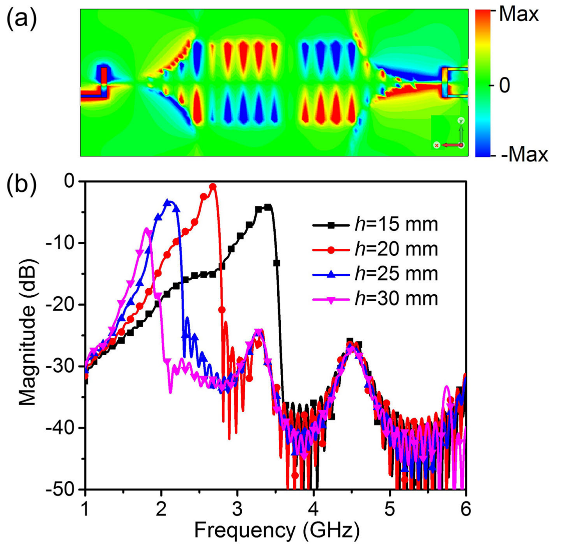

FIGURE 8. (a) The simulated *z*-component of *E*-field descriptions of the proposed filtering balun at 2 GHz, (b) simulated S_{21} (the same to S_{31}) of the proposed filtering balun under different values of *h*.

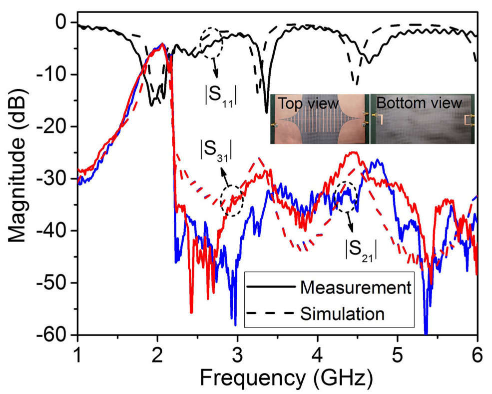

FIGURE 9. The photographs of the fabricated filtering balun and its simulated and measured results.

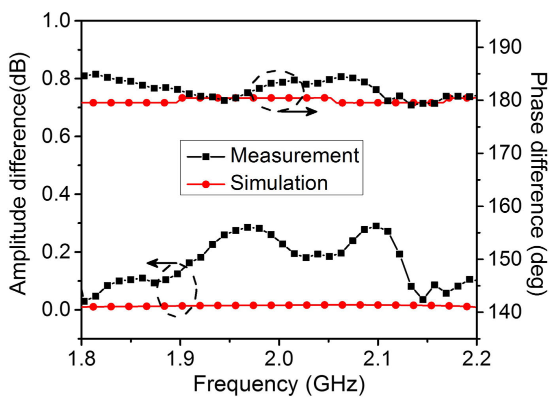

FIGURE 10. The simulated and measured results of amplitude difference and phase difference between the two balanced ports.

0.9 dB and 12 dB respectively over the filtering band. The unflatness of the passband is mainly caused by the slight radiation at the frequency near the intersection of the dispersion curve and light line [33]. Meanwhile, the higher stopband can extend beyond $3f_0$. The simulated and measured

TABLE 1. The comparison with previous works.

Ref.	f_0 (GHz)	IL (dB)	3-dB FBW	AD (dB)	PD (°)	Stopband width
[18]	4	2.0	31%	<0.6	<8	NA
[19]	2.78	1.2	23.4%	<0.5	<5	$2.3f_0$
[20]	2.02	1.1	3.45%	<1.0	<5	NA
[21]	2	3.3	12.4%	<0.9	<8	NA
This work	2	1.1	12.5%	<0.3	<5	$>3f_0$

amplitude difference (AD) and phase difference (PD) between the two balanced ports are plotted in Fig. 10. It shows that the PD between the two balanced ports varies within 180°±5° with an AD less than 0.3 dB in the designed passband. Table 1 compares the main performance parameters (where f_0 stands for center frequency) between the proposed filtering balun and some other previous works. It indicates that the proposed design features low IL, both good amplitude balance and out-of-phase property as well as wide stopband. In addition, this work provides a new approach to achieve filtering balun with controllable bandwidths of operation.

V. CONCLUSION

In this paper, a new approach to design filtering balun is reported based on symmetric SSPP structure. The odd mode in the symmetric SSPP strip and the microstrip-slotline cross-coupling structures are fully utilized to propagate balanced EM wave with 180° phase difference and equal magnitude. Meanwhile, to realize the effective conversion of the guided wave in slotline to the odd mode SSPP, a gradient transition structure is introduced. Filtering capability can be realized by the cut-off frequency of the propagation mode and the passband can be adjusted easily with the groove height of the SSPP structure while maintaining a high-efficient transmission. Based on these features, a prototype filtering balun is designed, fabricated, and experimentally tested which reveals good performances. The proposed concept may bring alternative design method for future microwave passive devices in communication systems.

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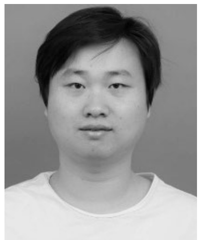
MINGZHU DU received the B.S. and M.Sc. degrees from the Department of Science and Technology, Nantong University, in 2012 and 2015, respectively. He is currently pursuing the Ph.D. degree in electromagnetic field and microwave engineering with the Department of Electronic Science and Engineering, Nanjing University, Nanjing, China. His research interests include metamaterial/metasurface, antenna, and microwave circuit.



KE CHEN (Member, IEEE) received the B.S. and Ph.D. degrees in electronic science and engineering from Nanjing University, Nanjing, China, in 2012 and 2017, respectively. He is currently a Research Fellow with the Department of Electronic Engineering, School of Electronic Science and Engineering, Nanjing University. His research interests include electromagnetic metamaterials and metasurfaces, and their applications to novel microwave functional devices.

JUNMING ZHAO (Member, IEEE) received the B.S. and Ph.D. degrees in electronic science and engineering from Nanjing University, Nanjing, China, in 2003 and 2009, respectively. Since 2009, he has been a Faculty Member with the Department of Electronic Engineering, School of Electronic Science and Engineering, Nanjing University, where he is currently a Professor. From January 2014 to January 2015, he was a Visiting Scholar with the Group of Antennas and Electromagnetics, School of Electronic Engineering and Computer Science, Queen Mary College, University of London. His research interests include electromagnetic metamaterials and metasurfaces, and their applications to novel microwave functional devices.

YIJUN FENG (Member, IEEE) received the M.Sc. and Ph.D. degrees from the Department of Electronic Science and Engineering, Nanjing University, in 1989 and 1992, respectively. Since 1992, he has been a Faculty Member with the Department of Electronic Engineering, School of Electronic Science and Engineering, Nanjing University, where he is currently a Full Professor. From September 1995 to July 1996, he was a Visiting Scientist with the Physics Department, Technical University of Denmark. From August 2001 to August 2002, he was a Visiting Researcher with the University of California at Berkeley. He has conducted more than twenty scientific research projects, including the National 973, the 863 Projects, and the National Natural Science Foundation projects in China. He has authored or coauthored over 160 journal articles and over 120 referred international conference papers. His research interests include electromagnetic metamaterial and application to microwave and photonic devices, electromagnetic wave theory, and novel microwave functional materials. He has received the 2010 Science and Technology Award (First grade) of Jiangsu Province, China, and the 1995 Scientific and Technological Progress Award by Minister of Education, China.