IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received August 10, 2020, accepted September 3, 2020, date of publication September 18, 2020, date of current version September 30, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3024596

An Ultra-Thin and Compact Band-Pass Filter Based on Spoof Surface Plasmon Polaritons

LIAORI JIDI, XIANGYU CAO, (Senior Member, IEEE), JUN GAO, HUANHUAN YANG, (Member, IEEE), SIJIA LI, AND TONG LI

Information and Navigation College, Air Force Engineering University, Xi'an 710077, China

Corresponding authors: Liaori Jidi (jidiliaorikdy@163.com) and Xiangyu Cao (xiangyucaokdy@163.com)

This work was supported in part by the National Natural Science Foundation of China under Grant 61671464, Grant 61471389, Grant 61701523, and Grant 61801508; in part by the Postdoctoral Innovative Talents Support Program of China under Grant BX20180375, and in part by the Natural Science Foundational Research Fund of Shaanxi Province, China, under Grant 2018JM6040 and Grant 2019JQ-103.

ABSTRACT In this work, we report an ultra-thin and compact SSPPs-based waveguide band-pass filter with metals etched on the top surface of substrate, and the side and bottom surfaces of substrate also are covered with metals. The size of this filter is $1.07\lambda_0 \times 0.32\lambda_0 \times 0.02\lambda_0$ (where λ_0 is the wavelength at center frequency). This proposed filter can inherit the merits of rectangular waveguide and SSPPs structure, and its lower cut-off frequency can be tuned by the width of rectangular waveguide, while the upper cut-off frequency can be tuned by the length of complementary comb-like structure. Gradient groove depths are also used to form a smooth transition from rectangular waveguide to SSPPs structure, realizing a good momentum match. The dispersion curves and electric field distributions have been thoroughly investigated to reveal the SSPP-based waveguide filter mechanism. A prototype is fabricated and measured. Both simulations and measurements validate that the band-pass filter proposed in this work has high-efficiency and low-loss transmission properties.

INDEX TERMS Band-pass filter, spoof surface plasmon polaritons, rectangular waveguide, tunable.

I. INTRODUCTION

At optical frequencies, metals behave as plasmons and have negative permitivities, while dielectric media have positive permittivities, so surface plasmon polaritons (SPPs) can be propagated in the interface between metal and dielectric media and decay exponentially in the direction vertical to the interface [1]–[4]. Because the interaction between Electromagnetic (EM) waves and plasmas is strong, the SPPs act as surface waves that are tightly confined near the interface and propagate parallel to the interface [4]–[8]. When frequencies are reduced down to terahertz (THz) and microwave frequencies, the metals behave as perfectly electric conductors (PECs), and smooth interfaces without period surface variations cannot support the propagation of SPPs anymore [5]–[10]. In the past several years, Spoof SPPs have been proposed to expand the researches of SPPs to lower frequencies. By decorating arrays of slits, holes, and blocks on the metallic surfaces to form artificial structured surfaces [5], [7], [9]–[12], some exotic SPPs-like characteristics can be realized at microwave frequencies, such as near field confinement and highly subwavelength localization. More importantly, the dispersion properties of SSPPs can be tailored by adjusting its geometrical parameters [3]–[6], making it attractive in the practical applications.

In 2013, T. J. Cui and his students proved that an ultra-thin corrugated metallic strip can guide the conformal SPP, indicating that the spoof SPP wave is able to propagate along arbitrarily curved surfaces across long distances with very low absorption and radiation loss [13]. Since then, researchers have proposed a series of periodic structures based on corrugated metallic wires to support the propagation of SSPPs [4], [6], [8], [10]–[12]. Especially in recent years, many kinds of functional devices based on corrugated SSPPs structures have been proposed. For example, various plasmonic transmission lines (TLs) have been developed [2], [15], [16], and their characteristics also have been thoroughly analyzed by others, these TLs based on SSPPs structures can be used to enhance the EM field confinement, reduce the crosstalk and improve the transmission efficiency.

The associate editor coordinating the review of this manuscript and approving it for publication was Wei E.I. Sha.

The low loss and high efficiency properties of SSPPs TLs inspire researchers to present different wireless devices, such as antennas [17]–[22], filters, power dividers [27]–[29] and couplers [30]–[31].

Some microwave filters based on the merits of SSPPs structures have been proposed, but among them the majorities are the low-pass filters [4], [8]–[12], [23]–[26]. Just a few works related to the SSPPs band-pass filters have been proposed. For example, [25] presents a suspended strip-line filter based on SSPPs and realizes miniaturized design, but it is a three-dimensional structure. [31] presents a band-pass filter by placing SSPPs sections beside a main SSPPs TL and introducing resonances, leading to transmission zeros to the main SSPPs TL, but this filter also is three-dimensional and its loss is a little high in the operation band. Moreover, most of the reported filters related with SSPPs TLs are based on single conductor transmission lines [4], [8], [10]–[12], [23]–[26], which etches metal on just one single surface of substrate, making it complicated to design or inconvenient to connect with the traditional two-conductor transmission lines.

In this work, we report a kind of simple ultra-thin and compact SSPPs-based waveguide filter with metals etched on the top surface of substrate, and the side and bottom surfaces of substrate also are covered with metals, which not only has high-efficiency and low-loss features but also realizes a controllable band-pass performance. Specifically, the cross section of this proposed band-pass filter shows a rectangular waveguide with a dielectric substrate inside and the sealed waveguide can confine most EM energies within the cavity. Under the fundamental TE_{10} mode, the waveguide behaves as a high-pass filter and the lower cut-off frequency of this proposed band-pass filter depends on the parameters of the cross section. By comparison, controlling the upper cut-off frequency of SSPPs-based band-pass filter is relatively easy, so we can change the asymptotic frequency of SSPPs structure to control the upper cut-off frequency. In order to make a better understanding of the physical mechanisms of the proposed filter, the dispersion relations and electric field distributions are carefully analyzed, and the characteristics of our proposed SSPPs-based band-pass filter are verified through both numerical simulations and experimental measurements. The proposed filter has the following several merits: (1) Compact and miniaturized size ($1.07\lambda_0 \times 0.32\lambda_0 \times 0.02\lambda_0$, where λ_0 is the wavelength at center frequency); (2) Working band is controllable by varying the geometrical parameters; (3) Covering the bottom surface of substrate with metals to make it convenient in the traditionally integrated circuits design; (4) High-efficiency and low-loss properties.

II. DESIGN AND ANALYSIS OF UNIT CELL

The unit cell proposed in this work is illustrated in Fig. 1 (a). This proposed unit cell has three layers: the top layer is a complementary symmetric comb-like metallic structures, in which the periodicity, slot width, and gap width between two comb-like structures are marked as p, a, and w_l, and the length of comb-like structure is denoted as h, the middle layer is a substrate, and the bottom layer is a metallic surface. The dielectric substrate is chosen as a commercial printed circuit board (PCB) with relative permittivity $\varepsilon_r = 4.3$ and the loss tangent tan$\delta = 0.001$, and its thickness t is 1mm, while the metal is chosen as copper with a thickness of 0.035mm. The dispersion relations of this proposed plasmonic structure can be tuned by adjusting the geometrical parameter h. To explore the propagation characteristics of SSPPs structure, we study the dispersion relations using the Eigen-mode solver of the commercial software, CST Microwave Studio. As displayed in Fig. 1(b), the boundary conditions of external area are set to periodic boundaries in the propagation direction of EM wave (z-direction), and in x- and y-directions the boundaries are set as perfectly electric conductors (PECs). To begin with, as illustrated in Fig. 1(b), the proposed structure acts as a rectangular waveguide because the boundaries in x-direction are set as PECs, and w and t represent the width and height of rectangular waveguide, respectively. For TE_{10} mode, the cut-off frequency can be calculated as:

$$f_c = (\pi/w)/(2\pi\sqrt{\mu\varepsilon}) \tag{1}$$

In the discussion of dispersion relations, we set w as 15.5mm, and then the f_c is 4.667GHz. For this work, because of the interaction between both sides of complementary symmetric comb-like metallic structure, there are even- and odd-mode SSPPs propagating along this symmetric SSPPs structure, and their electric field patterns in the cross-section surfaces are displayed in Fig. 1(c). We can conclude from Fig. 1(c) that electric field distributions of odd mode are anti-symmetric, while that of the even mode are symmetric. In order to guarantee that the EM waves propagated inside the rectangular cavity is TE_{10} mode, even-mode SSPPs have to be excited. The even-mode dispersion curves of this proposed SSPPs structure with respect to the parameter h are shown in Fig. 1(d). We notice that covering the bottom surface of substrate with metals does not deteriorate so much in maintaining the SSPPs properties, so we can still regard this structure as a plasmonic one, while the plasmonic structures reported in other works just etch metallic structures on a single surface of substrate. We can observe that the dispersion curves deviate obviously from the light and finally approaches the asymptotic frequencies, and the SSPPs waves can be tightly confined by the structured surface and propagate with very low loss. It can be concluded that the larger h is, the lower asymptotic frequency is.

The dispersion curves also have lower cut-off frequencies, and all the lower cut-off frequencies are the same under the same value of parameter w. The reason of the appearance of lower cut-off frequencies is that the proposed plasmonic structure acts as a rectangular waveguide, and the simulated lower cut-off frequency is 4.666GHz under the w of 15.5mm, which agrees well with the calculated one of 4.667GHz. When the value of h is set as 6mm, we draw the dispersion relations with respect to the parameter w, as illustrated in Fig. 1(e). We can conclude that the lower cut-off frequency can be tuned by the value of w, and the larger w is, the lower

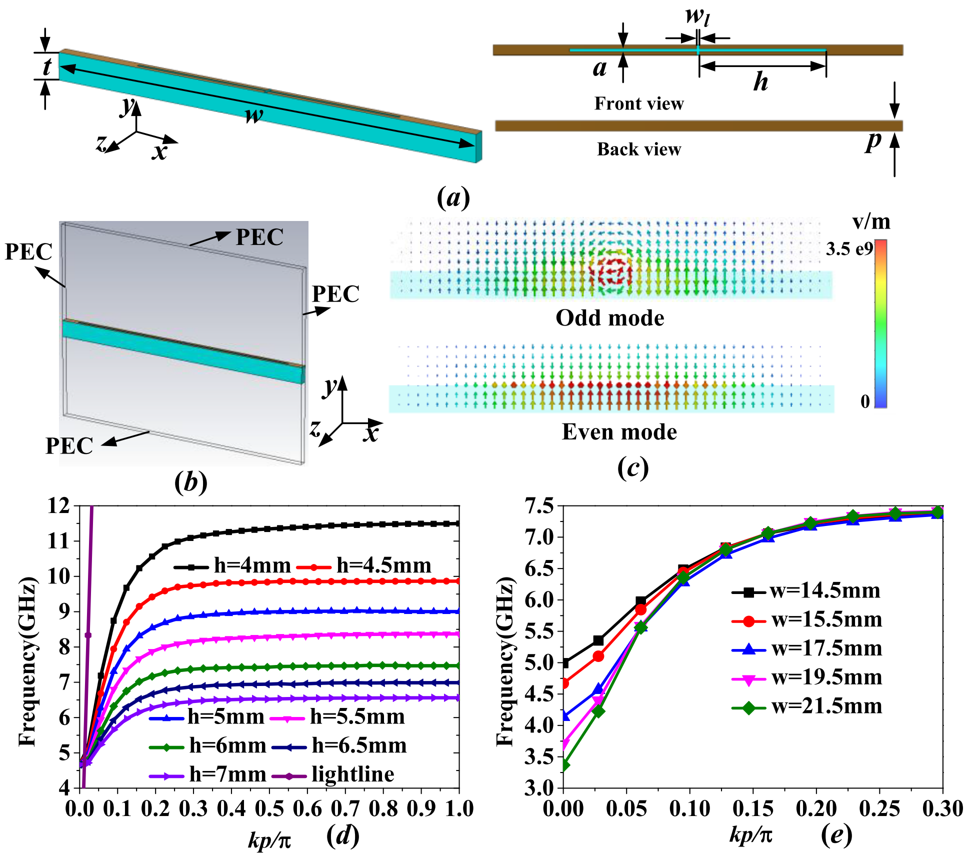

FIGURE 1. (a) Schematic configuration of proposed unit cell. The parameter dimensions are set as p=0.4mm, a=0.1mm, and w_l = 0.1mm. (b) Boundary conditions of the numerical eigenmode analysis. (c) E-field distributions of odd and even modes. (d) Dispersion relations of proposed SSPPs structure with different value of h when w is fixed as 15.5mm. (e) Dispersion relations proposed SSPPs structure with different values of w when h is set as 6mm.

the cut-off frequency is, while the asymptotic frequencies of the proposed complementary comb-like structure remain stable with different values of w. According to the analysis mentioned previously, we can conclude that the complementary comb-like structure is of band-pass characteristic, and the lower cut-off frequency can be adjusted by the parameter of w, while the upper cut-off frequency can be tuned by the parameter of h.

III. DESIGN OF BAND-PASS FILTER

The configuration of the proposed SSPP-based waveguide band-pass filter is sketched in Fig. 2(a). Particularly, in order to satisfy the PEC boundary set in the x-direction in Fig. 1(b), the majority parts of the side surfaces of this band-pass filter are covered with metals. The microstrip width w_s is chosen as 2.1mm to meet the 50Ω impedance of Subminiature Version A (SMA) connector. This structure has three parts. The first part is a transition section from microstrip line to rectangular waveguide, and the second part is the transition section from rectangular waveguide to SSPPs structure. The third part is used to propagate SSPPs waves. It can be observed from Fig. 1(d) that the deviation from the lightline becomes stronger with increase of parameter h, and the asymptotic frequency becomes lower. If we gradually increase the h from 0mm to h, the EM waves will be gradually confined near to the SSPPs structure, thus there will be a good momentum match between the rectangular waveguide and SSPPs structure.

In order to verify the relationship between the lower cut-off frequency of waveguide filter and w, when the h is fixed as 6mm, the simulated transmission coefficients of S21 with different w values are demonstrated. In Fig. 2(c), it is clearly observed that the cut-off frequency shifts toward lower value with the increase of w, while the upper cut-off frequencies remain stable under different w values, thus the lower cut-off frequency can be adjusted by the modification of width of rectangular waveguide, which is accordance with the theoretical analysis mentioned above. However, we note that the simulated 3-dB lower cut-off frequency under w of 15.5mm is around 5.1GHz, while the calculated one using Eq. (1) is 4.67GHz. To find out the reason which causes this deterioration, we also simulated the transmission properties of rectangular waveguide which removes the comb-like structure form the proposed waveguide filter, and its results are

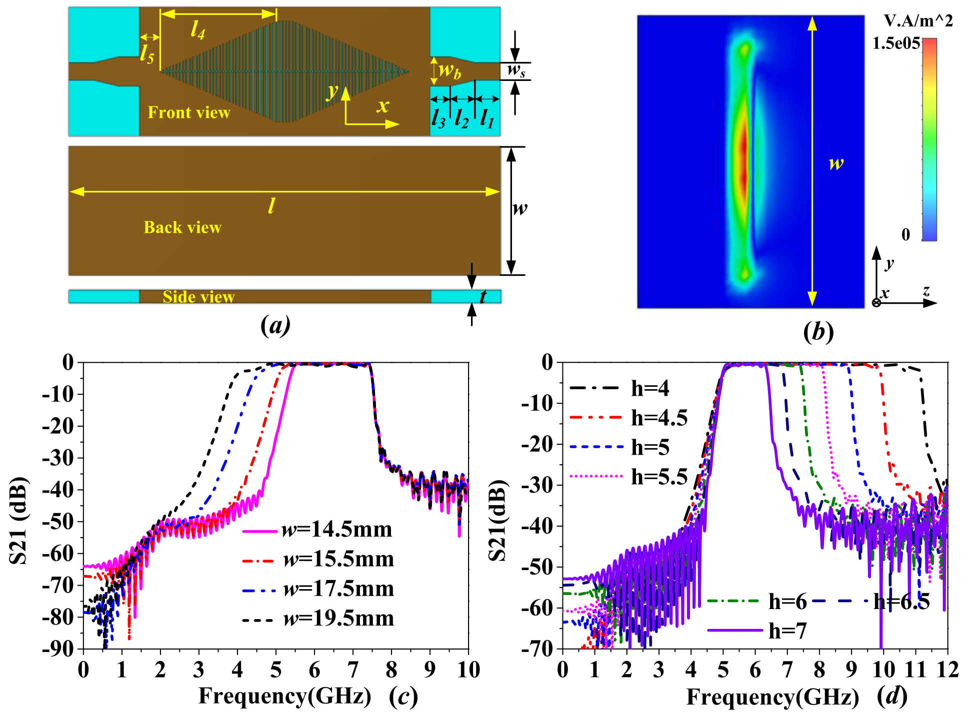

FIGURE 2. (a) Schematic configuration of the proposed band-pass filter. The detailed dimensions are: l = 52mm, l_1 = 3mm, l_2 = 3mm, l_3 = 2.5mm, l_4 = 14mm, l_5 = 2.5mm, w_s = 2.1mm, w_b = 3.5mm, w = 15.5mm. (b) The magnitudes of energy flows on cross section of *y-z* plane when *x*=0. (c) Simulated transmission coefficients with respect to different *w* values when *h* is fixed as 6mm. (d) Simulated transmission coefficients with respect to different *h* values when *w* is fixed as 15.5mm.

displayed in Fig. 3(b). We can observe that 3-dB cut-off frequency of rectangular waveguide under *w* of 15.5mm is around 4.76GHz, which is more closely to the theoretical one of 4.67GHz. From the above discussion, we can conclude that adding complementary comb-like structure to the waveguide can lead shift to the lower cut-off frequency. But anyway, we can design a certain lower cut-off frequency of waveguide filter by optimizing the parameter *w*, as shown in Fig. 2(c).

In order to verify the relationship between the upper cut-off frequency of waveguide filter and *h*, when the *w* is fixed as 15.5mm, the simulated transmission coefficients of S21 with different *h* values are displayed. Fig. 2(d) shows that the upper cut-off frequency can be tuned by different values of the length of comb-like structure, and the results are in accordance with the asymptotic frequencies displayed in Fig. 1(d). For example, the asymptotic frequency of SSPPs structure under *h* of 6mm is 7.47GHz, while the upper 3-dB cut-off frequency of proposed filter is 7.48GHz, and they agree well with each other.

In our design, the value of *w* and *h* are chosen as 15.5mm and 6mm, respectively. Based on the analysis above, the lower and upper 3-dB cut-off frequencies should be 5.1GHz and 7.48GHz, respectively. In order to realize a good performance of reflection coefficients (S11) of the proposed filter, all the parameters are optimized and the detailed dimensions are shown in Fig. 2(a) as well. This proposed filter is compact and miniaturized ($1.07\lambda_0 \times 0.32\lambda_0 \times 0.02\lambda_0$, where λ_0 is the wavelength at center frequency). To verify the functionality of the proposed configuration, the sample of the proposed filter is fabricated, as displayed in Fig. 3(d). The simulated and measured transmission and reflection coefficients are displayed in Fig. 3(c) for comparison. We find that the simulated and measured results are in good agreement with each other. The 3-dB transmission coefficient (S21) bandwidth of simulation is from 5.1GHz to 7.48GHz, while that of measurement is from 5.03GHz to 7.22GHz, and the highest S21 of simulation is up to -0.25dB, while that of measurement is up to -0.68dB. The reflection coefficients (S11) of both simulation and measurement are all less than -10dB. Additionally, it should be noted that compared with the simulated results, the measured ones show a little higher in-band insertion loss and poorer selectivity at the upper band and higher S11 at the whole operation band, which is caused by the parasitic properties of the SMA connector and substrate, the soldering imperfection, and the measurement imperfection. As expected, both simulated and measured results prove that the proposed filtering method for SSPPs TL is feasible.

In order to further show the excellent field confinement and good propagation characteristic of the proposed SSPP-based waveguide filter, the simulated magnitudes of energy flows on cross section of *y-z* plane when $x = 0$ and the simulated E_z-field patterns at 4.5, 5.5, 6, 6.5, 7 and 8GHz are also

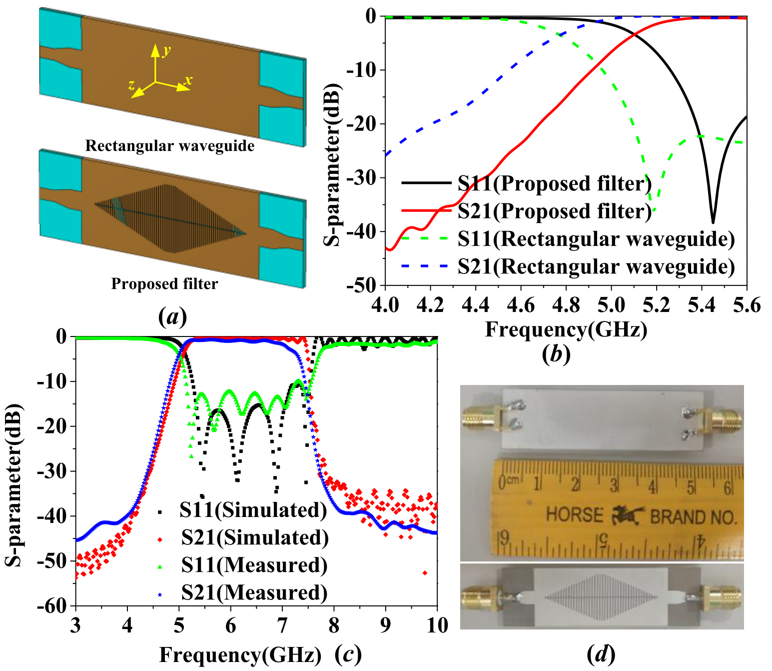

FIGURE 3. (a) The comparison between rectangular waveguide and the proposed filter. (b) The comparison of reflection and transmission coefficients between rectangular waveguide and the proposed filter. (c) The simulated and measured S parameters of the proposed band-pass filter. (d) The photograph of the fabricated filter.

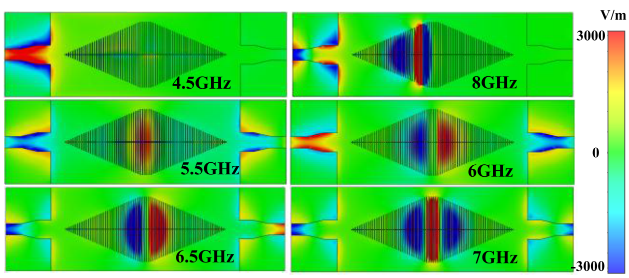

FIGURE 4. z-component electric field distributions of the proposed filter at 4.5, 5.5, 6, 6.5, 7 and 8GHz.

simulated and displayed in Fig. 2(b) and Fig. 4. We can observe from Fig. 2(b) that most of the EM energy is highly localized within the rectangular waveguide cavity and a small region above the proposed SSPPs-based waveguide filter. From Fig. 4, we can conclude that the even-mode SSPPs waves can be propagated through the SSPPs structure efficiently at 5.5, 6, 6.5, and 7GHz, which are located in the passband of the proposed filter. The SSPPs waves cannot be propagated through the rectangular waveguide part at 4.5GHz, while the SSPPs waves cannot be propagated through the SSPPs part, which also can verify that the lower and upper cut-off frequencies are adjusted by the parameters of w and h, respectively. From those discussions, we can conclude that the proposed structure can support the propagation of SSPPs waves on its surface, exhibiting potential applications in SSPPs devices.

IV. CONCLUSION

In conclusion, an ultra-thin and compact SSPPs waveguide filter is proposed in this work, which has a different working principle with its former counterparts. The rectangular waveguide acts as a high-pass filter, while the SSPPs TL acts as a low-pass filter. We combined the merits of these two structures into an integration to design a pass-band filter. The lower cut-off frequency can be tuned by the width of rectangular waveguide, while the upper cut-off frequency can be tuned by the length of comb-like structure. Gradient groove depths are used to form a smooth transition from rectangular waveguide to SSPPs structure, thus realizing a good momentum match. The dispersion curves and electric field distributions have been thoroughly investigated to reveal the SSPP-based waveguide filter mechanism. Finally, based on the analysis, a prototype is fabricated and measured. Both simulated and measured results validate the proposed design concept. This work has a very promising future in the development of SSPPs functional devices and circuits in the THz and microwave frequencies.

ACKNOWLEDGMENT

The authors would like to thank Mr. D. Zhai from AFEU for his help in preparing the manuscript.

REFERENCES

[1] Z. Gao, L. Wu, F. Gao, Y. Luo, and B. Zhang, "Spoof plasmonics: From metamaterial concept to topological description," *Adv. Mater.*, vol. 30, no. 31, May 2018, Art. no. 1706683.

[2] W. X. Tang, H. C. Zhang, H. F. Ma, W. X. Jiang, and T. J. Cui, ''Concept, theory, design, and applications of spoof surface plasmon polaritons at microwave frequencies,'' *Adv. Opt. Mater.*, vol. 7, no. 1, Jan. 2019, Art. no. 1800421.
[3] P. H. He, H. C. Zhang, X. Gao, L. Y. Niu, W. X. Tang, J. Lu, L. P. Zhang, and T. J. Cui, ''A novel spoof surface plasmon polariton structure to reach ultra-strong field confinements,'' *Opto-Electron. Adv.*, vol. 2, no. 6, 2019, Art. no. 19000101.
[4] H. F. Ma, X. Shen, Q. Cheng, W. X. Jiang, and T. J. Cui, ''Broadband and high-efficiency conversion from guided waves to spoof surface plasmon polaritons,'' *Laser Photon. Rev.*, vol. 8, no. 1, pp. 146–151, Jan. 2014.
[5] H. C. Zhang, S. Liu, X. P. Shen, L. H. Chen, L. M. Li, and T. J. Cui, ''Broadband amplification of spoof surface plasmon polaritons at microwave frequencies,'' *Laser Photon. Rev.*, vol. 9, pp. 1–8, Nov. 2014.
[6] H. Xiang, Y. Meng, Q. Zhang, F. F. Qin, J. J. Xiao, D. Han, and W. Wen, ''Spoof surface plasmon polaritons on ultrathin metal strips with tapered grooves,'' *Opt. Commun.*, vol. 356, pp. 59–63, Dec. 2015.
[7] Y. J. Zhou, Q. X. Xiao, and B. Jia Yang, ''Spoof localized surface plasmons on ultrathin textured MIM ring resonator with enhanced resonances,'' *Sci. Rep.*, vol. 5, no. 1, Sep. 2015, Art. no. 14819.
[8] X. Gao, L. Zhou, Z. Liao, H. F. Ma, and T. J. Cui, ''An ultra-wideband surface plasmonic filter in microwave frequency,'' *Appl. Phys. Lett.*, vol. 104, no. 19, May 2014, Art. no. 191603.
[9] D. Zhang, K. Zhang, Q. Wu, R. Dai, and X. Sha, ''Broadband high-order mode of spoof surface plasmon polaritons supported by compact complementary structure with high efficiency,'' *Opt. Lett.*, vol. 43, no. 13, pp. 3176–3179, Jul. 2018.
[10] B. C. Pan, Z. Liao, J. Zhao, and T. J. Cui, ''Controlling rejections of spoof surface plasmon polaritons using metamaterial particles,'' *Opt. Express*, vol. 22, pp. 13940–13950, Jun. 2014.
[11] X. Gao, L. Zhou, and T. J. Cui, ''Odd-mode surface plasmon polaritons supported by complementary plasmonic metamaterial,'' *Sci. Rep.*, vol. 5, no. 1, p. 9250, Mar. 2015.
[12] Z. Xu, S. Liu, S. Li, H. Zhao, L. Liu, and X. Yin, ''Tunneling of spoof surface plasmon polaritons through magnetoinductive metamaterial channels,'' *Appl. Phys. Express*, vol. 11, no. 4, Mar. 2018, Art. no. 042002.
[13] X. Shen, T. J. Cui, D. Martin-Cano, and F. J. Garcia-Vidal, ''Conformal surface plasmons propagating on ultrathin and flexible films,'' *Proc. Nat. Acad. Sci. USA*, vol. 110, no. 1, pp. 40–45, Jan. 2013.
[14] J. Zhang, H.-C. Zhang, X.-X. Gao, L.-P. Zhang, L.-Y. Niu, P.-H. He, and T.-J. Cui, ''Integrated spoof plasmonic circuits,'' *Sci. Bull.*, vol. 64, no. 12, pp. 843–855, Jun. 2019.
[15] H. C. Zhang, P. H. He, W. X. Tang, Y. Luo, and T. J. Cui, ''Planar spoof SPP transmission lines,'' *IEEE Microw. Mag.*, vol. 20, no. 11, pp. 73–91, Nov. 2019.
[16] J. Y. Yin, J. Ren, L. Zhang, H. Li, and T. J. Cui, ''Microwave vortex-beam emitter based on spoof surface plasmon polaritons,'' *Laser Photon. Rev.*, vol. 12, no. 3, Jan. 2018, Art. no. 1600316.
[17] A. Kianinejad, Z. N. Chen, and C.-W. Qiu, ''A single-layered Spoof-Plasmon-Mode leaky wave antenna with consistent gain,'' *IEEE Trans. Antennas Propag.*, vol. 65, no. 2, pp. 681–687, Feb. 2017.
[18] G. S. Kong, H. F. Ma, B. G. Cai, and T. J. Cui, ''Continuous leaky-wave scanning using periodically modulated spoof plasmonic waveguide,'' *Sci. Rep.*, vol. 6, no. 1, p. 29600, Jul. 2016.
[19] D.-F. Guan, P. You, Q. Zhang, Z.-H. Lu, S.-W. Yong, and K. Xiao, ''A wide-angle and circularly polarized beam-scanning antenna based on microstrip spoof surface plasmon polariton transmission line,'' *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 2538–2541, 2017.
[20] M. Wang, H. F. Ma, W. X. Tang, S. Sun, and T. J. Cui, ''Leaky-wave radiations with arbitrarily customizable polarizations based on spoof surface plasmon polaritons,'' *Phys. Rev. A, Gen. Phys.*, vol. 12, no. 1, Jul. 2019, Art. no. 014036.
[21] J. J. Xu, H. C. Zhang, Q. Zhang, and T. J. Cui, ''Efficient conversion of surface-plasmon-like modes to spatial radiated modes,'' *Appl. Phys. Lett.*, vol. 106, no. 2, Jan. 2015, Art. no. 021102.
[22] H. C. Zhang, Q. Wang, Y. Luo, L. Liu, P. H. He, J. Lu, L. P. Zhang, J. Xu, L. Liu, F. Gao, and T. J. Cui, ''A wide-angle broadband converter: From odd-mode spoof surface plasmon polaritons to spatial waves,'' *IEEE Trans. Antennas Propag.*, vol. 67, no. 12, pp. 7425–7432, Dec. 2019.
[23] J. Wang, L. Zhao, Z.-C. Hao, and T. J. Cui, ''An ultra-thin coplanar waveguide filter based on the spoof surface plasmon polaritons,'' *Appl. Phys. Lett.*, vol. 113, no. 7, Aug. 2018, Art. no. 071101.
[24] W. Feng, Y. Feng, W. Yang, W. Che, and Q. Xue, ''High-performance filtering antenna using spoof surface plasmon polaritons,'' *IEEE Trans. Plasma Sci.*, vol. 47, no. 6, pp. 2832–2837, Jun. 2019.
[25] S. Liao, C. Qi, and Q. Xue, ''Effective bandpass filtering for spoof surface plasmon polariton transmission lines,'' *Appl. Phys. Express*, vol. 12, no. 5, May 2019, Art. no. 054501.
[26] H. C. Zhang, P. H. He, X. Gao, W. X. Tang, and T. J. Cui, ''Pass-band reconfigurable spoof surface plasmon polaritons,'' *J. Phys., Condens. Matter*, vol. 30, no. 13, Mar. 2018, Art. no. 134004.
[27] B. Wu, H.-R. Zu, B.-Y. Xue, Y.-T. Zhao, and Q. S. Cheng, ''Flexible wideband power divider with high isolation incorporating spoof surface plasmon polaritons transition with graphene flake,'' *Appl. Phys. Express*, vol. 12, no. 2, Feb. 2019, Art. no. 022008.
[28] S.-Y. Zhou, S.-W. Wong, J.-Y. Lin, L. Zhu, Y. He, and Z.-H. Tu, ''Four-way spoof surface plasmon polaritons splitter/combiner,'' *IEEE Microw. Wireless Compon. Lett.*, vol. 29, no. 2, pp. 98–100, Feb. 2019.
[29] S. Zhou, J.-Y. Lin, S.-W. Wong, F. Deng, L. Zhu, Y. Yang, Y. He, and Z.-H. Tu, ''Spoof surface plasmon polaritons power divider with large isolation,'' *Sci. Rep.*, vol. 8, no. 1, pp. 59471–59478, Apr. 2018.
[30] J. Y. Yin, J. Ren, H. C. Zhang, B. C. Pan, and T. J. Cui, ''Broadband frequency-selective spoof surface plasmon polaritons on ultrathin metallic structure,'' *Sci. Rep.*, vol. 5, no. 1, pp. 81651–81655, Feb. 2015.
[31] R. Wang, J. Wang, Y. Han, Y. Li, J. Zhang, X. Tian, A. Zhang, and S. Qu, ''Miniaturized suspended strip-line bandpass filter based on spoof surface plasmon polaritons,'' *J. Phys. D, Appl. Phys.*, vol. 52, no. 32, Jun. 2019, Art. no. 325101.

LIAORI JIDI was born in Sichuan, China. He received the B.S. degree from the Electronic and Information College, Tongji University, in 2016, and the M.S. degree from the Information and Navigation Institute, Air Force Engineering University of CPLA, China, in 2018, where he is currently pursuing the Ph.D. degree in electromagnetic field and microwave technology. He was the commencement student speaker of Tongji University, in 2016. He has authored or coauthored more than ten technical journal articles and conference papers. In his research, he specializes in spoof surface plasmon polaritons and its applications on antennas and RCS reduction techniques.

XIANGYU CAO (Senior Member, IEEE) received the B.S. and M.S. degrees from the Air Force Missile Institute (AFMI), Xi'an, China, in 1986 and 1989, respectively, and the Ph.D. degree in from the Institute, Air Force Engineering University (AFEU), in 1999. She became an Associate Professor, in 1996. From 1999 to 2002, she was engaged with a Postdoctoral Research, Xidian University, China. She was a Senior Research Associate with the Department of Electronic Engineering, City University of Hong Kong, from 2002 to 2003. She is currently a Professor with AFEU. She has authored or coauthored more than 120 technical journal articles and conference articles. Her research interests include computational electromagnetic, smart antennas, electromagnetic metamaterial, and their antenna applications.

JUN GAO received the B.S. and M.S. degrees from the Air Force Missile Institute (AFMI), Xi'an, China, in 1984 and 1987, respectively. In 1987, he joined AFMI as an Assistant Teacher and became an Associate Professor, in 2000. He is currently a Professor with Air Force Engineering University (AFEU). His research interests include smart antennas, electromagnetic metamaterial, and their antenna applications.

HUANHUAN YANG (Member, IEEE) received the B.S., M.S., and Ph.D. degrees from Air Force Engineering University (AFEU), Xi'an, China, in 2010, 2012, and 2016, respectively. He was a Joint-Supervision Ph.D. Student with AFEU and Tsinghua University. He is currently a Lecturer with AFEU. His research interests include reconfigurable antenna, reflectarray, metasurface, and RCS reduction technique.

SIJIA LI received the B.Eng. degree in electronics and information engineering from Guangxi University, Nanning, China, in 2009, and the M. Eng. degree in information and telecommunication engineering from Air Force Engineering University, Xi'an, China, in 2011, where he is currently pursuing the Ph.D. degree in electromagnetic field and microwave technology with the Information and Navigation Institute. He has authored or coauthored more than 40 scientific papers in major journals and international conferences. His research interest includes the broadband perfect metamaterial absorber and its application for RCS reduction of antennas.

TONG LI received the B.S. and Ph.D. degrees in electronic and information engineering from Xidian University, Xi'an, China, in 2010 and 2015, respectively. She is currently a Lecturer with Air Force Engineering University. Her current research interests include ultra-wideband communication devices, reconfigurable antennas, and metasurface.