Received September 22, 2017, accepted October 21, 2017, date of publication October 31, 2017, date of current version December 5, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2768481

A Multi-Layer Spoof Surface Plasmon Polariton Waveguide With Corrugated Ground

PEI HANG HE, HAO CHI ZHANG, (Student Member, IEEE), WEN XUAN TANG, (Member, IEEE), ZHENG XING WANG, RUI TING YAN, AND TIE JUN CUI, (Fellow, IEEE)

State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096, China

Corresponding author: Tie Jun Cui (tjcui@seu.edu.cn)

This work was supported in part by the National Natural Science Foundation of China under Grant 61501117, Grant 61631007, Grant 61302018, Grant 61401089, Grant 61571117, and Grant 61501112, and in part by the 111 Project under Grant 111-2-05.

ABSTRACT Due to the unique properties of field confinement and enhancement, spoof surface plasmon polaritons (SPPs) are considered as special modes to break many challenges in traditional electronic and microwave engineering. Ultrathin corrugated metallic structure offers an easy fabrication method to realize spoof SPP waveguides on substrate, and has been proved to have many merits in recent years. Lately, a programmable and coding spoof SPP waveguide loaded by active elements was presented, which makes it possible to control SPPs in real time. However, this programmable SPPs waveguide suffers from the limited loadable space and hence can hardly achieve more complex controlling functions. On the other hand, the existing methods to excite spoof SPPs require large conversion structures, which are unadoptable in modern integrated circuits. In this paper, we propose a new type of spoof SPP waveguide composed of a metallic strip and corrugated ground with an open loadable space for large-scale and complex controlling networks. A new conversion structure is presented to achieve high-efficiency transition from the traditional microstrip to the SPP waveguide without using extra space. Both numerical simulations and experiments indicate the outstanding performance of the new spoof SPP waveguide. The proposed structure is also convenient to connect with active devices due to its multi-conductor nature. Hence, the proposed structure may find wide applications in SPP-based integrated circuits and systems in the future.

INDEX TERMS Surface plasmon polaritons (SPPs), programmable, coding, conversion structure, integrated circuit.

I. INTRODUCTION

Surface plasmon polaritons (SPPs) are a kind of special electromagnetic (EM) surface waves and have attracted great attentions due to their potential applications in both scientific and engineering areas. The natural SPPs exist on the interface between dielectric and metal at the visible or ultraviolet (UV) frequencies where the permittivity of metal is negative [1], and propagate along the interface while decay exponentially in the vertical direction of the interface [2]. Therefore, SPPs possess excellent properties of strong field confinement and enhancement, which can be applied into many devices and systems such as the super-resolution imaging [3], [4], high-quality and miniaturized sensors [1], [5], and photovoltaics [6].

However, at lower frequencies like the far infrared, terahertz and microwave frequencies, metal behaves like perfectly electric conductor (PEC) instead of plasma with negative permittivity. Thus natural SPPs cannot be excited in these low frequency bands. To overcome this problem and replicate the unique properties of SPPs into the common electronic engineering, plasmonic metamaterials which can support a kind of SPP-like surface waves, named as spoof SPPs or designer SPPs, were presented [7]–[17]. The plasmonic metamaterials can be constructed by metallic surfaces decorated by subwavelength one-dimensional (1D) arrays of grooves [18] and two-dimensional (2D) arrays of pits and hills [7], [19]. Ultrathin corrugated metallic strip which can be fabricated by printed-circuit board (PCB) technology has become the popular plasmonic metamaterial transmission line (TL) nowadays [20], [21]. This kind of TL has the merits of easy fabrication, low-loss [22], interference suppression [23], and great flexibility [20].

The corresponding excitation structure of the spoof SPP TL from a coplanar waveguide (CPW), which is composed of gradient corrugation grooves and flaring ground [24], was also reported. Although this method achieves broadband and high-efficiency conversion between spatial modes in CPW to SPPs, the width and area of the conversion section is too large, which is inconvenient in modern integrated circuits (ICs) and miniaturized systems. Moreover, the transmission performance of single-conductor spoof SPP TLs can be controlled by changing the geometric parameters, but cannot be reconfigured after fabrication.

In view of this, programmable and coding SPP TLs have been presented [25], which are loaded with active elements inside each unit structure, and can be controlled dynamically through digital inputs. Although this type of coding SPP TL allows us to reconfigure its properties and achieve some fundamental digital-analog devices such as SPP logical gate and SPP digital phase shifter, it is difficult to integrate huger and complex controlling networks into the SPP TLs for more flexible functions due to their limited loadable space. Thus the technique has to be further developed to meet more requirements of modern information systems.

In order to overcome these problems, we firstly present a new spoof SPP TL structure composed of adjacently periodic metallic patches and a strip on the opposite side of dielectric substrate respectively, which provides a possibility to easily connect with additionally active elements or complicated controlling network. We investigate the dispersion properties of the SPP TL with different geometric parameters by Eigen-mode simulations. Then we propose an extremely compact conversion structure to realize smooth conversion between spatial wave modes in microstrip (MS) and SPPs, which is validated by the transmission performance using full-wave simulations. We fabricate two samples of the proposed SPP TLs with different geometric parameters, and detect their S-parameters and near-field distributions based on the home-made near-field scanner. Both numerical simulations and measurement results indicate that SPPs are excited efficiently through the compact structure. Owing to the multi-conductor nature [26], [27], the proposed SPP TL can also be connected with active devices conveniently. Therefore, this new SPP TL and conversion structure may be widely used in SPP circuits and integrated systems in the future.

II. RELATED WORK

A. NEW SPP TL AND DISPERSION ANALYSIS

We present a new spoof SPP TL structure. Fig. 1a and 1b are configurations of the top and bottom sides of the proposed SPP TL, respectively, where the loadable area for additional controlling modules is represented by the area encircled by red imaginary lines. For previous spoof SPP TLs used in Ref. [25], as shown in Fig. 3c, the loadable area is only the narrow gaps between metallic patches and strip, while the new structure can load a much larger and complex controlling network in an open area. Fig. 1c is a conversion structure between the new SPP TL and traditional MS with impedance of 50Ω. The material of the substrate is Rogers RT5880 with the relative permittivity of $\varepsilon_r = 2.2$ and loss

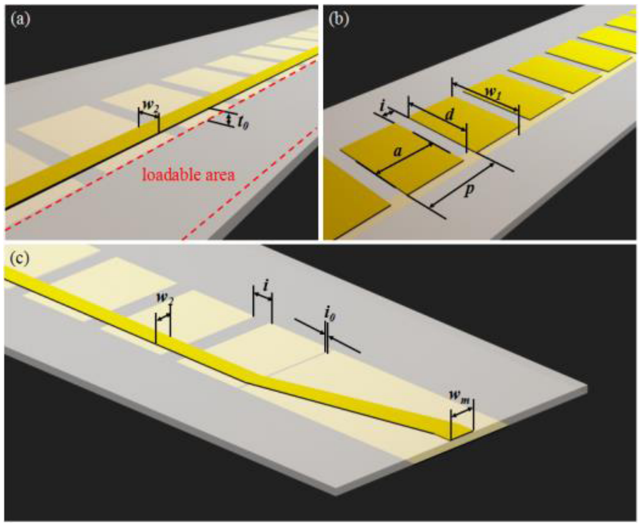

FIGURE 1. The detailed geometric configuration of the proposed new spoof SPPs TL with corrugated ground. (a)The top view of the new spoof SPPs TL, in which the width of the metallic strip is w_2, the thickness of the substrate is t_0 and the area encircled by red imaginary lines is the loadable area. (b)The bottom view of the new spoof SPPs TL, in which the width of the metallic patches is w_1, the length of the metallic patches is a, the equivalent depth of grooves is d, the period of the TL is p and the interval between two adjust patches is i. (c) The configuration of the conversion structure of this new spoof SPPs TL, in which the width of microstrip is w_m and the interval of first gap is i_0.

tangent of $\tan\delta = 0.0009$. The thickness of the substrate is $t_0 = 0.508$mm. The width of MS with impedance 50Ω is $w_m = 1.5$mm. The period of TL is p, the width and length of metallic patches are w_1 and a, respectively, the interval of adjacent patches is $i = p\text{-}a$, the width of metallic strip is w_2, and the equivalent depth of groove, which is an important parameter in previous spoof SPP TLs, is $d = w_1\text{-}w_2$. Note that the metallic strip is located at the edge rather than the center of TL. The MS sections and conversion structures are at the two ends of the whole structure.

Then we investigate the dispersion properties of the spoof SPP TL structure with different geometric parameters using the Eigen-mode simulation of commercial software, CST Microwave Studio, and the results are shown in Fig. 2. The dispersion curves of these spoof SPP TLs deviate from the light line gradually as the frequency increases, and reach to the cutoff frequencies asymptotically, which are typical dispersion characteristics of natural SPPs. From Fig. 2a, we can find that as the equivalent depth d increases and the other parameters are fixed as $w_2 = 1$mm, $p = 5$mm and $a = 4.8$mm, the dispersion curve deviates further from the light line and the cutoff frequency decreases, which implies the stronger field confinement and enhancement. The simulated dispersion curves of this structure with different parameters of strip width w_2, period p, and interval of patches i are also sketched in Fig. 2b-d, respectively. And it can be clearly observed that the changes of period p and interval i impact the dispersion curve much less than the equivalent depth d.

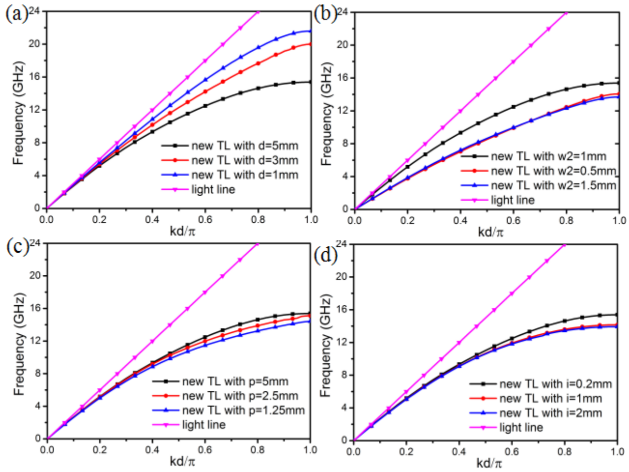

FIGURE 2. The simulated dispersion curves for the new spoof SPPs TLs with different geometric parameters. (a)Dispersion diagrams of the new spoof SPPs TLs with different equivalent depth of grooves d. (b)Dispersion diagrams of the new spoof SPPs TLs with different strip widths w_2. (c)Dispersion diagrams of the new spoof SPPs TLs with different periods p. (d)Dispersion diagrams of the new spoof SPPs TLs with different intervals i.

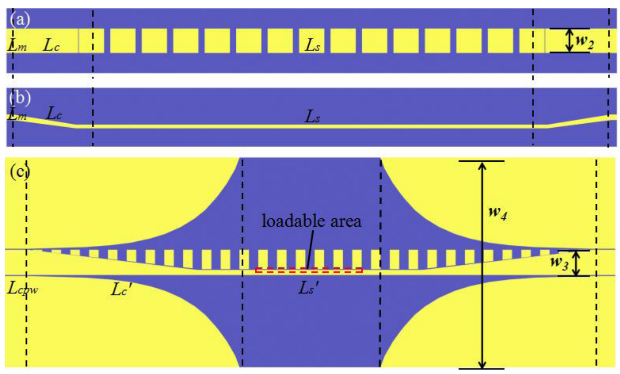

FIGURE 3. Schematic diagram of the conversion structures of two types of spoof SPPs TLs. (a)The top configurations of the whole transmission structure of the new spoof SPPs TL, in which the length of MS is $L_m = 1$mm, the length of the new spoof SPPs TL is $L_s = 70$mm, the length and width of conversion section is $L_c = 12.5$mm and $w_2 = 6$mm, respectively. (b)The bottom configurations of the whole transmission structure of the new spoof SPPs TL. (c)The configurations of the whole transmission structure of the CPW-excited spoof SPPs TL, where the length of CPW is $L_{cpw} = 3.5$mm, the length and width of the CPW-excited spoof SPPs TL is $L_s' = 24$mm and $w_3 = 7.2$mm, the length and width of conversion section is $L_c' = 33$mm and $w_4 = 50$mm, respectively, and the area encircled by red imaginary lines is the loadable area.

B. ULTRA-COMPACT CONVERSION STRUCTURE

In order to excite spoof SPPs EM modes on our new TL, we construct an ultra-compact conversion structure to achieve smooth and rapid conversions between spoof SPPs and MS guided waves, as shown in Fig. 3. In this work, the length of MS with 50Ω impedance is $L_m = 1$mm, the length of the new spoof SPPs TL is $L_s = 70$mm, and the length of conversion section is $L_c = 12.5$mm. The conversion structure is composed of a tiny interval between MS and the first metallic patch, equal to 0.1mm, and a curved metallic strip. Note that the wider metallic strip on the bottom of substrate in Fig. 1a serves as the ground of MS section while the narrower metallic strip on the top of substrate in Fig. 1b serves as the guiding strip. The width of the conversion structure is the same as that of the spoof SPP TL. In another word, no additional width is required in the transition. The full-wave simulation of the whole two-port structure, in which the geometric parameters of the spoof SPP TL is fixed as $p = 5$mm, $a = 4.8$mm, $w_1 = 6$mm, $w_2 = 1$mm, $i = p\text{-}a = 0.2$mm and $d = w_1\text{-}w_2 = 5$mm, is performed by the CST Microwave Studio and the result of S-parameters is shown in Fig. 4a. It can be easily observed that a high-efficiency conversion between spoof SPPs and MS guided EM waves is achieved, implying good matching of wavenumber and impedance. And the cutoff frequency of this TL is about 15.4GHz, which is identical to the simulated result of Eigen-mode simulation. In some special cases, designer need a larger interval between the metallic patches as loadable space to realize some customized functions [28]. Thus, we also investigate the conversion performance of the same conversion structures for the new spoof SPPs TL with $i = 1$mm and $i = 2$mm, and the simulated result is shown in Fig. 4b. Theoretically, the end of the conversion structure connected with the new spoof SPP TL can be approximatively regarded as a period of similar TL with $i = 0.1$mm. According to the dispersion analysis in Fig. 2a, the mismatch of wavenumbers of the spoof SPP TLs with different i is not severe, so the conversion is supposed to be smooth. Simulated S-parameters in Fig. 4b demonstrate outstanding performance of the conversion structure under these cases, and the cutoff frequency moves to about 14.3 and 14 GHz, respectively, which agrees with the previous dispersion analysis very well. The longer conversion section with gradually varied intervals may achieve tiny improvement of the transmission efficiency, but a larger area will be required, which is unworthy in minimized circuits and systems. Thus, this conversion structure possesses great adaptation for the proposed spoof SPP TLs with different geometric parameters.

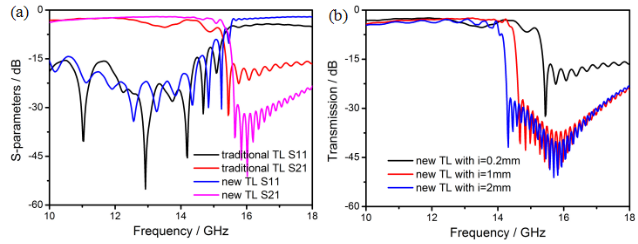

FIGURE 4. Simulated S-parameters of two new spoof SPPs TLs with different i of 0.2mm, 1mm and 2mm and the traditional CPW-excited spoof SPPs TL. (a)Simulated S-parameters of the new spoof SPPs TL with $i = 0.2$mm and the traditional CPW-excited spoof SPPs TL. (b)Simulated transmission coefficients of the new spoof SPPs TLs with $i = 0.2$mm, $i = 1$mm and $i = 2$mm.

To visually show the compact advantage of the conversion, we simulate a traditional CPW-excited spoof SPP TL structure, as shown in Fig. 3c where the length of CPW with 50Ω impedance is $L_{cpw} = 3.5$mm, the length of the new spoof SPPs TL is $L_s' = 24$mm, the width of the guiding strip is $w_3 = 7.2$mm, and the length and width of the conversion section are $L_c' = 33$mm and $w_4 = 50$mm, respectively.

The simulated S parameters of the CPW-excited transmission structure are shown in Fig. 4a as a comparison to the new structure. It can be observed that the new spoof SPP TL can provide slightly better conversion efficiency than the traditional CPW-excited one, while its conversion structure is much shorter and more compact, requiring no additional cumbersome width. Thus, the proposed spoof SPP TL and ultra-compact conversion structure achieve the universal, high-efficiency and rapid transition between traditional MS guided EM mode and spoof SPPs mode.

FIGURE 5. **Two samples of the new structures with different interval *i* of 0.2mm and 1mm. (a)The top view of this two samples. (b)The bottom view of this two samples.**

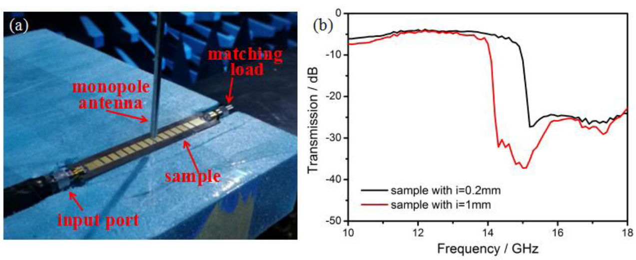

FIGURE 6. **The photograph of the home-made near-field scanner and measured S-parameters of two new spoof SPPs TLs. (a)The photograph of the home-made near-field scanner, composed of a VNA and a monopole antenna installed in a mechanical platform which can move under the control of stepper motor. (b)Measured S-parameters of two new spoof SPPs TLs with different *i* of 0.2mm and 1mm.**

C. EXPERIMENTS

To experimentally verify the outstanding performance of the proposed structure, we fabricate two samples of the new TLs with the same geometric parameters but different intervals *i* of 0.2mm and 1mm on the substrate Rogers RT5880 of 0.508mm thickness, as shown in Fig. 5. In this experiment, we use vector network analyzer (VNA) AV3672B to obtain the reflection (S11) and transmission (S12) coefficients of these two spoof SPP TLs. In order to connect the whole structure with VNA, we weld standard SMA connectors onto all ports of these two samples. The measured S parameters of these two samples are shown in Fig. 6b, and it is obvious that the conversion has a very high efficiency.

For visualizing the conversion process and transmission of EM waves, we plot the near-field distribution of electric field at 1mm above these two samples at 12GHz and 18GHz by simulation and the results are shown in Fig. 7a-d, indicating the propagating of a SPPs-like EM mode at 12GHz and the interdict at 18GHz. We also measured the near-field distribution of electric field of these two samples at 12GHz and 18GHz based on a home-made near-field scanner, composed of a VNA and a monopole antenna installed in a mechanical platform which can move under the control of stepper motor, as shown in Fig. 6a. In the experiments, one port of the sample is connected with one port of VNA, the other port of the sample is connected with the matching impedance, and the

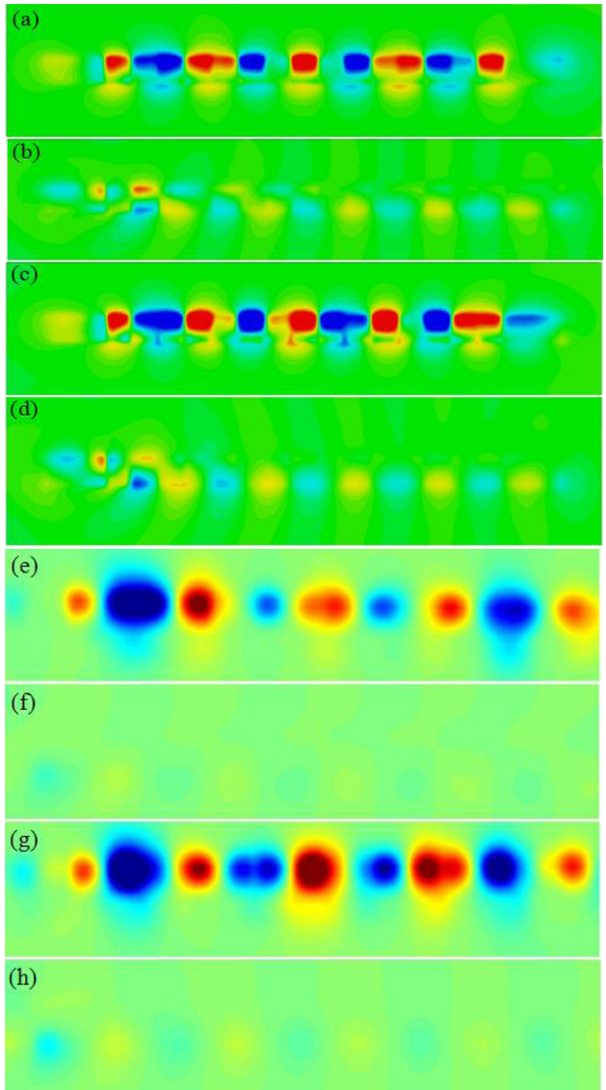

FIGURE 7. **The simulated and measured results of near-field distribution of electric field of these two samples at the frequency of 12GHz and 18GHz. (a)Simulated results of the near-field distribution of the sample with $i = 0.2$mm at 12GHz. (b)Simulated results of the near-field distribution of the sample with $i = 0.2$mm at 18GHz. (c)Simulated results of the near-field distribution of the sample with $i = 1$mm at 12GHz. (d)Simulated results of the near-field distribution of the sample with $i = 1$mm at 18GHz. (e)Measured results of the near-field distribution of the sample with $i = 0.2$mm at 12GHz. (f)Measured results of the near-field distribution of the sample with $i = 0.2$mm at 18GHz. (g)Measured results of the near-field distribution of the sample with $i = 1$mm at 12GHz. (h)Measured results of the near-field distribution of the sample with $i = 1$mm at 18GHz.**

other port of VNA is connected with the monopole antenna which is about 1mm above the samples. The measured results of near-field distributions of these two samples at 12GHz and 18GHz are shown in Fig. 7e-h, which are of great agreement with the simulated results.

III. CONCLUSION

The concept of programmable plasmonic metamaterial offers us the ability to reconfigure the dispersion properties of spoof SPPs and engineer the behaviors of SPP waves, such as the transmission and phase shift. More flexible manipulations of the programmable metamaterials require more complicated active controlling modules. It is still a challenge, however, to load complex controlling modules into the SPP TLs because of their limited loadable space.

In this work, we proposed a new type of spoof SPP TL composed of metallic adjacent periodic patches and a strip on the opposite side of the dielectric substrate. The dispersion property of the new spoof SPP TL can be controlled by adjusting its geometric parameters or loading active modules. Owing to its geometric structure, the new spoof SPP TL offers an open loadable space for larger controlling network to achieve more complex controlling strategy and functions. The corresponding MS conversion structure constructed by covering the guiding strip and corrugated ground is not only highly efficient and universal, but also much more compact than the traditional CPW conversion structure, which offers us great convenience to apply spoof SPPs to ICs and chips. This structure can also be connected with active devices due to its multi-conductor nature. Hence, the proposed spoof SPP TLs have potentials to be widely used in ICs and other customized applications.

ACKNOWLEDGMENT

(Pei Hang He and Hao Chi Zhang contributed equally to this work.)

REFERENCES

[1] W. L. Barnes, A. Dereux, and T. W. Ebbesen, "Surface plasmon subwavelength optics," *Nature*, vol. 424, no. 6950, pp. 824–830, Aug. 2003.

[2] S. A. Maier, *Plasmonics: Fundamentals and Applications*. New York, NY, USA: Springer, 2007.

[3] A. C. Jones, R. L. Olmon, S. E. Skrabalak, B. J. Wiley, Y. N. Xia, and M. B. Raschke, "Mid-IR plasmonics: Near-field imaging of coherent plasmon modes of silver nanowires," *Nano Lett.*, vol. 9, pp. 2553–2558, Jul. 2009.

[4] N. Fang, H. Lee, C. Sun, and X. Zhang, "Sub-diffraction-limited optical imaging with a silver superlens," *Science*, vol. 308, pp. 534–537, Apr. 2005.

[5] J. N. Anker, W. P. Hall, O. Lyandres, N. C. Shah, J. Zhao, and R. P. Van Duyne, "Biosensing with plasmonic nanosensors," *Nature Mater.*, vol. 7, no. 6, pp. 442–453, Jun. 2008.

[6] A. Polman and H. A. Atwater, "Photonic design principles for ultrahigh-efficiency photovoltaics," *Nature Mater.*, vol. 11, pp. 174–177, Feb. 2012.

[7] J. B. Pendry, L. Martín-Moreno, and F. J. Garcia-Vidal, "Mimicking surface plasmons with structured surfaces," *Science*, vol. 305, pp. 847–848, Aug. 2004.

[8] G. Goubau, "On the excitation of surface waves," *Proc. IRE*, vol. 40, pp. 865–868, Jul. 1952.

[9] A. P. Hibbins, B. R. Evans, and J. R. Sambles, "Experimental verification of designer surface plasmons," *Science*, vol. 308, pp. 670–672, Apr. 2005.

[10] F. J. Garcia-Vidal, L. Martín-Moreno, and J. B. Pendry, "Surfaces with holes in them: New plasmonic metamaterials," *J. Opt. A, Pure Appl. Opt.*, vol. 7, no. 2, pp. S97–S101, Feb. 2005.

[11] B. K. Juluri, S. C. Lin, T. R. Walker, L. Jensen, and T. J. Huang, "Propagation of designer surface plasmons in structured conductor surfaces with parabolic gradient index," *Opt. Exp.*, vol. 17, no. 4, pp. 2997–3006, Feb. 2009.

[12] R. Elliott, "On the theory of corrugated plane surfaces," *Trans. IRE Prof. Group Antennas Propag.*, vol. 2, no. 2, pp. 71–81, Apr. 1954.

[13] S. A. Maier, S. R. Andrews, L. Martín-Moreno, and F. J. García-Vidal, "Terahertz surface plasmon-polariton propagation and focusing on periodically corrugated metal wires," *Phys. Rev. Lett.*, vol. 97, p. 176805, Oct. 2006.

[14] P. Nagpal, N. C. Lindquist, S. H. Oh, and D. J. Norris, "Ultrasmooth patterned metals for plasmonics and metamaterials," *Science*, vol. 325, pp. 594–597, Jul. 2009.

[15] Y. J. Zhou, Q. Jiang, and T. J. Cui, "Bidirectional bending splitter of designer surface plasmons," *Appl. Phys. Lett.*, vol. 99, p. 111904, Sep. 2011.

[16] J. G. Rivas, "Terahertz: The art of confinement," *Nature Photon.*, vol. 2, pp. 137–138, Dec. 2008.

[17] Q. Gan, Z. Fu, Y. J. Ding, and F. J. Bartoli, "Ultrawide-bandwidth slow-light system based on THz plasmonic graded metallic grating structures," *Phys. Rev. Lett.*, vol. 100, p. 256803, Jun. 2008.

[18] Q. Gan, Y. Gao, K. Wagner, D. Vezenov, Y. J. Ding, and F. J. Bartoli, "Experimental verification of the rainbow trapping effect in adiabatic plasmonic gratings," *Proc. Nat. Acad. Sci. USA*, vol. 108, pp. 5169–5173, Oct. 2011.

[19] C. R. Williams, S. R. Andrews, S. A. Maier, A. I. Fernández-Domínguez, L. Martín-Moreno, and F. J. García-Vidal, "Highly confined guiding of terahertz surface plasmon polaritons on structured metal surfaces," *Nature Photon.*, vol. 2, pp. 175–179, Mar. 2008.

[20] 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, pp. 40–45, Jan. 2013.

[21] X. Shen and T. J. Cui, "Planar plasmonic metamaterial on a thin film with nearly zero thickness," *Appl. Phys. Lett.*, vol. 102, p. 211909, May 2013.

[22] H. C. Zhang, Q. Zhang, J. F. Liu, W. Tang, Y. Fan, and T. J. Cui, "Smaller-loss planar SPP transmission line than conventional microstrip in microwave frequencies," *Sci. Rep.*, vol. 6, Mar. 2016, Art. no. 23396.

[23] H. C. Zhang, T. J. Cui, Q. Zhang, Y. Fan, and X. Fu, "Breaking the challenge of signal integrity using time-domain spoof surface plasmon polaritons," *ACS Photon.*, vol. 2, pp. 1333–1340, Aug. 2015.

[24] 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, pp. 146–151, Jan. 2014.

[25] H. C. Zhang, T. J. Cui, J. Xu, W. Tang, and J. F. Liu, "Real-time controls of designer surface plasmon polaritons using programmable plasmonic metamaterial," *Adv. Mater. Technol.*, vol. 1, p. 1600202, Nov. 2016.

[26] H. C. Zhang, S. Liu, X. Shen, L. H. Chen, L. Li, and T. J. Cui, "Broadband amplification of spoof surface plasmon polaritons at microwave frequencies," *Laser Photon. Rev.*, vol. 9, pp. 83–90, Jan. 2015.

[27] H. C. Zhang, Y. Fan, J. Guo, X. Fu, and T. J. Cui, "Second-harmonic generation of spoof surface plasmon polaritons using nonlinear plasmonic metamaterials," *ACS Photon.*, vol. 3, pp. 139–146, Dec. 2015.

[28] S. Zhao, H. C. Zhang, J. Zhao, and W. X. Tang, "An ultra-compact rejection filter based on spoof surface plasmon polaritons," *Sci. Rep.*, vol. 7, Sep. 2017, Art. no. 10576.

PEI HANG HE received the B.S. degree from the University of Electronic Science and Technology of China, Chengdu, China, in 2017. He is currently pursuing the M.S. degree with Southeast University, Nanjing, China. His research interests include surface plasmonic polaritons, and metamaterials and milimeter waves theories and technologies.

HAO CHI ZHANG (S'15) was born in Zhejiang, China, in 1991. He received the B.Eng. degree in electrical engineering from the University of Electronic Science and Technology of China, Chengdu, China, in 2013. He is currently pursuing the Ph.D. degree in electromagnetic and microwave technology from Southeast University, Nanjing, China. His current research interests include microwave and millimeter-wave circuits and antennas technology, surface plasmons, and metamaterials.

WEN XUAN TANG (S'10–M'13) received the B.Sc. degree in electronic engineering and the M.Sc. degree in electromagnetic field and microwave technology from Southeast University, Nanjing, China, in 2006 and 2009, respectively, and the Ph.D. degree in electromagnetics from the Queen Mary University of London, U.K., in 2012. In 2012, she joined the School of Information Science and Engineering, Southeast University, as a Lecturer, and then became an Associate Professor in 2017. She has authored or co-authored an edited book on metamaterials, two book chapters, and over 30 technical articles in highly ranked journals, including the IEEE Transactions on Antenna and Propagation, the *New Journal of Physics*, *Optics Express*, the *Applied Physics Letters*, and *Light Science and Applications*. Her main research interests include metamaterials and their applications, and microwave devices and antennas.

ZHENG XING WANG is a native of Anqing city and has lived in Anhui, China, since 1995. Since 2013, he had studied in Xidian University. He majored in electromagnetic wave propagation and antenna and minored in management science. His grades earned him National Scholarship for encouragement. He is currently pursuing the master's degree with Southeast University.

RUI TING YAN was born in Inner Mongolia, China, in 1995. She received the B.S. degree in electronic information engineering from Xidian University, China, in 2017. She is currently pursuing the Ph.D. degree with the State Key Laboratory of Millimeter Waves, Southeast University, Nanjing, China.

TIE JUN CUI (M'98–SM'00–F'15) received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Xidian University, Xi'an, China, in 1987, 1990, and 1993, respectively. In 1993, he joined the Department of Electromagnetic Engineering, Xidian University, and was promoted to Associate Professor in 1993. From 1995 to 1997, he was a Research Fellow with the Institut fur Hochstfrequenztechnik und Elektronik, University of Karlsruhe, Germany. In 1997, he joined the Center for Computational Electromagnetics, Department of Electrical and Computer Engineering, University of Illinois at Urbana–Champaign, first as a Post-Doctoral Research Associate and then a Research Scientist. In 2001, he became a Cheung-Kong Professor with the Department of Radio Engineering, Southeast University. Since 2013, he has been a Representative of People's Congress of China.

He is the first author of the books *Metamaterials–Theory, Design, and Applications* (Springer, 2009) and *Metamaterials: Beyond Crystals, Non-crystals, and Quasicrystals* (CRC Press, 2016). He has authored over 400 peer-review journal papers in science, PNAS, *Nature Communications*, the *Physical Review Letters*, *Advanced Materials*, and IEEE transactions. His research interests include metamaterials, computational electromagnetic, wireless power transfer, and millimeter wave technologies, which have been cited by over 17000 times (H-Factor 66). According to Elsevier, he is one of the Most Cited Chinese Researchers. He received the Research Fellowship from the Alexander von Humboldt Foundation, Bonn, Germany, in 1995, the Young Scientist Award from the International Union of Radio Science in 1999, the Cheung Kong Professor under the Cheung Kong Scholar Program by the Ministry of Education, China, in 2001, the National Science Foundation of China for Distinguished Young Scholars in 2002, the Special Government Allowance by the Department of State, China, in 2008, the Award of Science and Technology Progress from the Shaanxi Province Government in 2009, the May 1st Labour Medal by the Jiangsu Province Government in 2010, the First Prize of Natural Science from Ministry of Education, China, in 2011, and the Second Prize of National Natural Science, China, in 2014. His research have been selected as one of the Optics in 2016 by the *Optics and Photonics News Magazine* (OSA), 10 Breakthroughs of China Optics in 2016, 10 Breakthroughs of China Science in 2010, Best of 2010 in the *New Journal of Physics*, the Research Highlights in Europhysics News, the *Journal of Physics D: Applied Physics*, the *Applied Physics Letters*, and Nature China. His work has been reported by Nature News, Science, MIT Technology Review, Scientific American, and New Scientists.

Dr. Cui is an active reviewer for science, nature materials, nature photonics, nature physics, nature communications, physical review letters, advanced materials, and a series of IEEE transactions. He served as the General Co-Chair of the International Workshops on Metamaterials (META'2008 and META'2012), and the TPC Co-Chair of the Asian Pacific Microwave Conference (APMC'2005) and the Progress in Electromagnetic Research Symposium (PIERS'2004). He was an Associate Editor of the IEEE Transactions on Geoscience and Remote Sensing and a Guest Editor of *Science China–Information Sciences*. He served as an Editorial Staff for the *IEEE Antennas and Propagation Magazine*, and on the editorial boards of *Progress in Electromagnetic Research* and the *Journal of Electromagnetic Waves and Applications*.