Invited Paper

A Compact terahertz spoof surface plasmon polaritons transmission line

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Abstract: In this paper, a terahertz on-chip transmission line based on spoof surface plasmon polaritons (SSPPs) is proposed and demonstrated through advanced InP technology. In order to reduce the occupied area of the conventional grooves structure SSPPs, a folded structure SSPPs is employed. Simulated results show that the occupied area of the folded SSPPs is reduced by up to 70.2% compared with the conventional grooves SSPPs structure under the same asymptotic frequency. In addition, an efficient excitation of the folded SSPPs transmission line is realized by a ground coplanar waveguide (GCPW) through a gradient transition structure. Simulated results show that the insertion loss of the SSPPs transmission line is less than 2.25 *dB/mm* at the frequency of 300 *GHz*, and the return loss is better than 15 *dB*, which also has an inherent low-pass filtering feature. This work has great significance for the terahertz plasmons semiconductor integrated circuits.

Keywords: Spoof surface plasmon polaritons; Transmission line; InP technology; Terahertz; On-chip

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1. Introduction

In recent years, with the gradual maturity of semiconductor transistor technology, terahertz (100 *GHz*-10 *THz*) monolithic integrated circuit (TMIC) has been rapidly developed, which has practical applications in wireless communication, nondestructive testing, medical imaging, electronic countermeasures, and precision guidance [1-4]. Terahertz on-chip transmission line is the basis of the TIMC to achieve information perception, transmission, and detection. Conventional terahertz on-chip transmission lines, such as microstrip lines, coplanar waveguides, and grounded coplanar waveguides, have inevitable dielectric loss and electromagnetic (EM) crosstalk [5-8]. To fundamentally solve this problem, it is necessary to modify the spatial distribution characteristics of the transmission mode.

Surface plasmon polaritons (SPPs) are surface waves generated by the interaction between electromagnetic waves and free electrons at the metal-medium interface. Due to the unique sub-wavelength field confinement and enhancement properties, SPPs have been widely used in super-resolution imaging, sensing, detection and miniaturized photonic circuits [9-12]. Typical SPPs are only generated in visible or infrared light, Nonetheless, in 2004, Pendry et al. made a breakthrough in that the SPPs can be generated in microwave and terahertz bands under the metal metamaterial surfaces. Because their dispersion characteristics are similar to typical SPPs and can be flexibly controlled by the geometric parameters of the metamaterial surface, they are named Spoof SPPs (SSPPs) [13-14]. The inherent field confinement capability of SSPPs can fundamentally solve the contradiction between circuit miniaturization and electromagnetic compatibility. Therefore, the SSPPs are expected to be a solution for further breakthroughs in terahertz integrated circuits. Due to the superior characteristics of SSPPs, a series of SSPPs transmission lines with different structures, such as metal groove, hole, and ring ripple have been studied [15-16]. However, the three-dimensional structure of the transmission line is enormous and difficult to combine with the planar circuit. In recent years, in order to realize the miniaturization and integration of the plasmons devices, ultra-thin SSPPs transmission line with planar groove structure has been proposed and studied, and a variety of microwave planar integrated plasmons devices based on this transmission line have been developed, such as filter, frequency divider, antenna, amplifier, and frequency multiplier [17-28].

In this paper, an advanced InP process is investigated for terahertz monolithic integrated circuits, and a compact SSPPs transmission line with folded structure is proposed under the semiconductor process. The dispersion of SSPPs unit cells is analyzed and compared with conventional groove structure SSPPs under the same asymptotic frequency, the footprint of the proposed folded SSPPs is reduced by 70.2%.

2. Design methods

As shown in Fig. 1, an advanced InP technology is employed, which is very suitable for terahertz device design with the advantages of wide band gap, high thermal conductivity, high electron saturation rate, excellent high frequency and power performance. In the architecture, all circuit structures are designed in a three-layer metal system interconnected through metallic vias. The top metal (M3) and the middle metal (M2) are available to support the signal transmission, and the bottom metal serves as a ground plane. Two benzocyclobutene (BCB) layers with the relative permittivity of 2.7 are utilized to separate the metal layers, and the thickness of BCB layers is 1.4 μm and 2 μm, respectively. In this design, the top metal M1 with the thickness of 2 μm is utilized as the signal transmission layer owning to its high-current capability. The middle metal M2 with the thickness of 0.5 μm and the metal–insulator-metal (MIM) SiN capacitors can be omitted.

The conventional groove structure SSPPs unit cell and proposed folded structure SSPPs unit cell are depicted in Fig. 2 (a) and Fig. 2 (b), respectively. In this design, the length of groove h = 90 μm, the period p = 60 μm, the length of folded line L = 12 μm, the width W_0 = 8 μm, W = 4 μm. The dispersion curves of the SSPPs unit structure are calculated by eigen-mode simulations of the commercial electromagnetic simulation software CST Microwave Studio. As shown in Fig. 2 (c), the dispersion curves of the groove structure SSPPs and folded structure SSPPs are overlapping, and all deviate significantly from the light line, which means that their wave vectors are greater than the ones in free space, and the slow wave propagates within about 0.47 *THz*. Evidently, at the same asymptotic frequency, the footprint of the groove structure SSPPs unit cell is 188×60 μm^2, while that of the folded structure SSPPs unit cell is only 56×60 μm^2, and the footprint is decreased by 70.2%. This is because the dispersion characteristic of SSPPs is primarily determined by its relative groove depth. As the relative groove depth increases, the asymptotic frequency of SSPPs gradually decreases, which causes the stronger field confinement and the lower electromagnetic crosstalk.

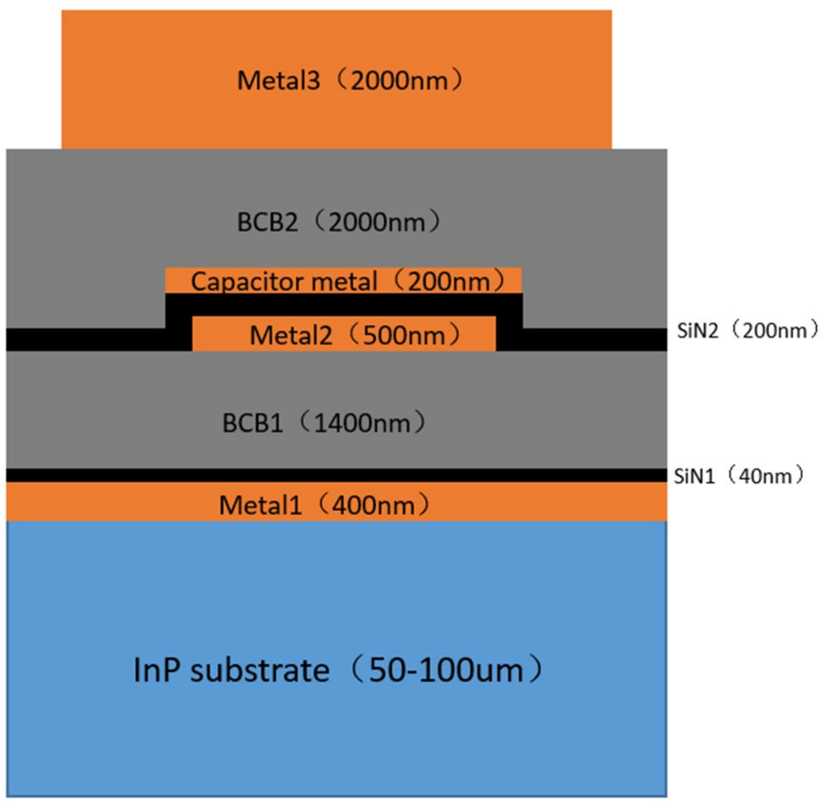

Fig. 1 Stack-up of the employed InP technology

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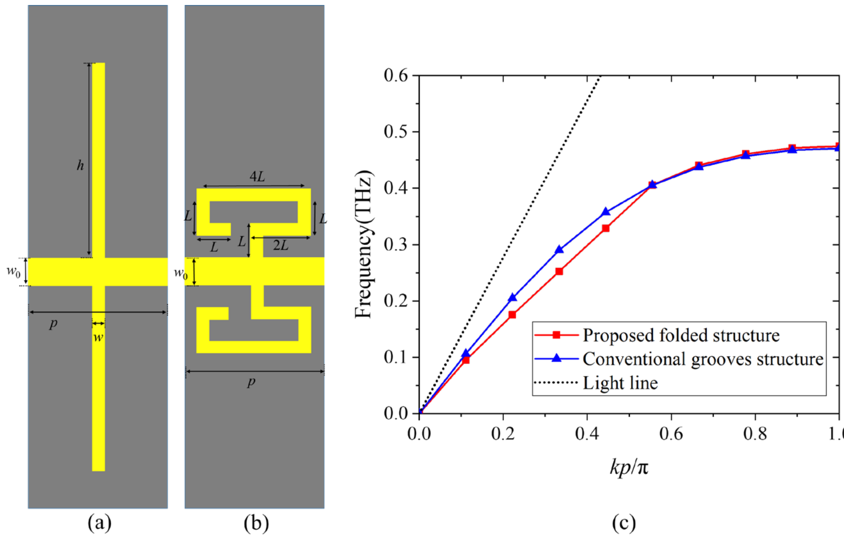

Fig. 2 The SSPPs unit cell and dispersion curves. (a) Layout of the grooves structure SSPPs unit cell; (b) Layout of the folded structure SSPPs unit cell. (c) Dispersion curves of the grooves structure SSPPs unit cell and folded structure SSPPs unit cell.

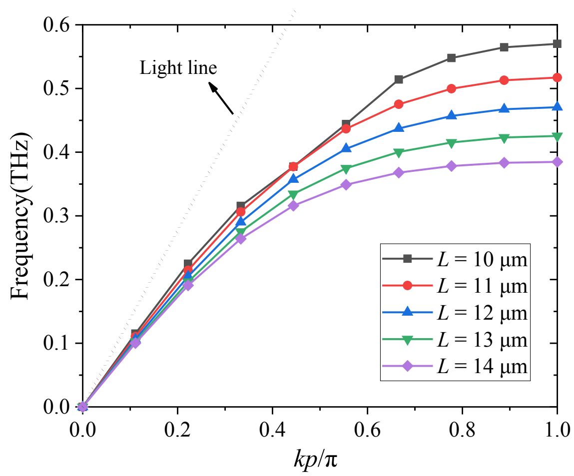

Fig. 3 Simulated dispersion curves of the folded structure SSPPs unit cell under the different lengths of the folded line *L*.

In addition, the relationship between the length of the folded line *L* and the dispersion curves of SSPPs is evaluated. As shown in Fig. 3, as the length of folded line *L* gradually increases from 10 *μm* to 14 *μm*, the asymptotic frequency of SSPPs gradually decreases from about 0.57 *THz* to 0.38 *THz*. Consequently, the dispersion characteristics of folded SSPPs can be flexibly adjusted by modifying the length of folded line *L*.

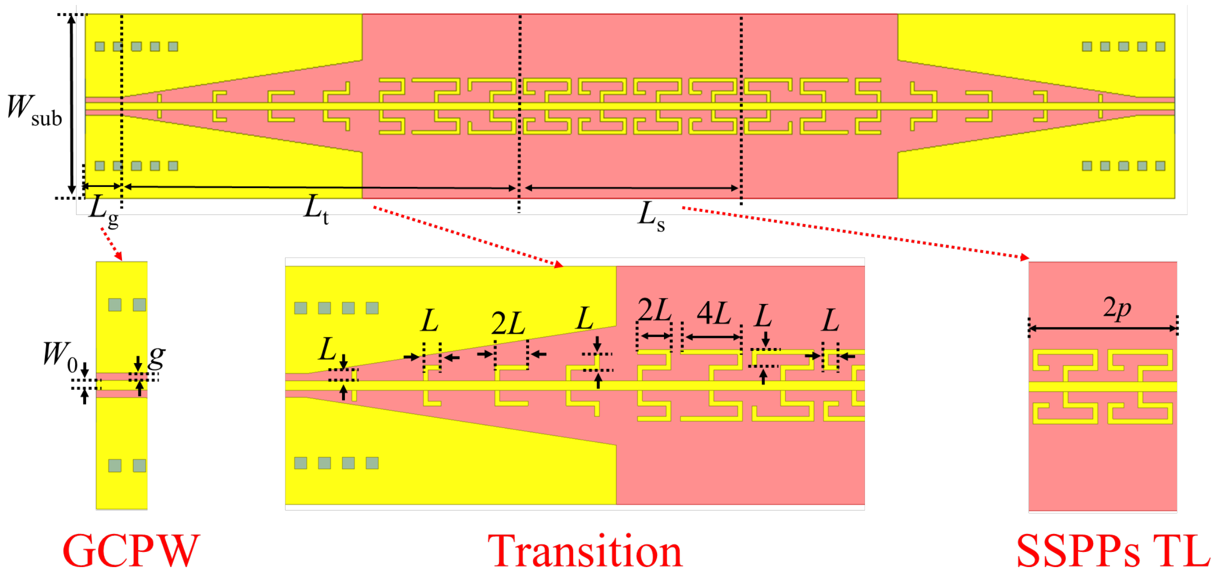

Fig. 4 Schematic configuration of the proposed terahertz on-chip transmission line based on SSPPs.

Based on the folded structure SSPPs unit cell, an on-chip terahertz transmission line is constructed as shown in Fig. 4. The transmission line is composed of three parts: grounded coplanar waveguide (GCPW), mode conversion (Transition), and SSPPs periodic array (SSPPs TL). The overall size of the transmission line is 1180 μm×200 μm. As the input/output feeding part of SSPPs, the characteristic impedance of the GCPW is 50 Ohm, the line width is the same as the line width of SSPPs W_0, gap width g = 6 μm, length L_g = 50 μm. The grounding of GCPW is realized by connecting the top metal M3 and bottom metal M1 through rectangular metallized holes. A gradient folded SSPPs structure and flaring ground are utilized to achieve impedance and momentum matching between GCPW and SSPPs TL. As shown in the transition part in Fig. 4, the period of the transition unit cell is the same as the one of the folded SSPPs unit cell p, and the length of the folded line in the longitudinal and transverse directions gradually increases from L respectively, and the step is fixed at L. The whole transition part is composed of seven gradient folded SSPPs unit cells with an overall length of L_t = 420 μm, and the SSPPs TL part is composed of nine folded SSPPs unit cells with an overall length of L_s = 240 μm.

The S-parameters of the proposed folded SSPPs transmission line are simulated. In the simulation, the THz signal is fed directly into the GCPW through the specified excitation waveguide port, and the open boundary is applied in all directions except the back ground to simulate the real on-wafer test setup. As shown in Fig. 5, the SSPPs transmission line shows low-pass filtering characteristics consistent with its dispersion characteristics. In addition, the insertion loss of the SSPPs transmission line is less than 2.25 dB / mm at the frequency of 300 GHz, and the return loss is better than 15 dB.

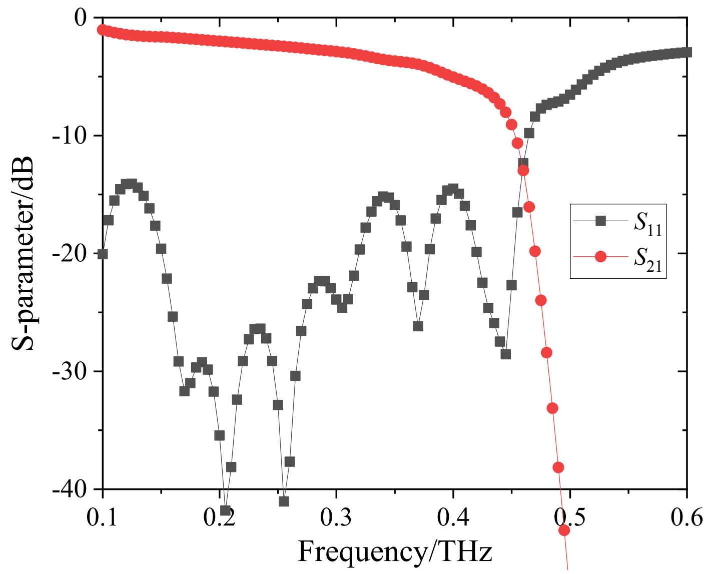

Fig. 5 Simulated results of the proposed terahertz on-chip transmission line based on SSPPs（$|S_{21}|$：insertion loss；$|S_{11}|$：return loss）.

To get more insight into the transmission characteristics of the proposed terahertz on-chip SSPPs TL, the electric field distributions in 300 *GHz* and 600 *GHz* are simulated. As shown in Fig. 7, the electric field at 300 *GHz* will not be cut off in the whole structure, i.e., the terahertz signal fed by GCPW is smoothly transferred to the SSPPs transmission line. Nevertheless, the electric field at 600 *GHz* attenuates greatly within the SSPPs unit cell and is ultimately completely cut off, which further verifies the inherent low-pass cutoff characteristics of the SSPPs.

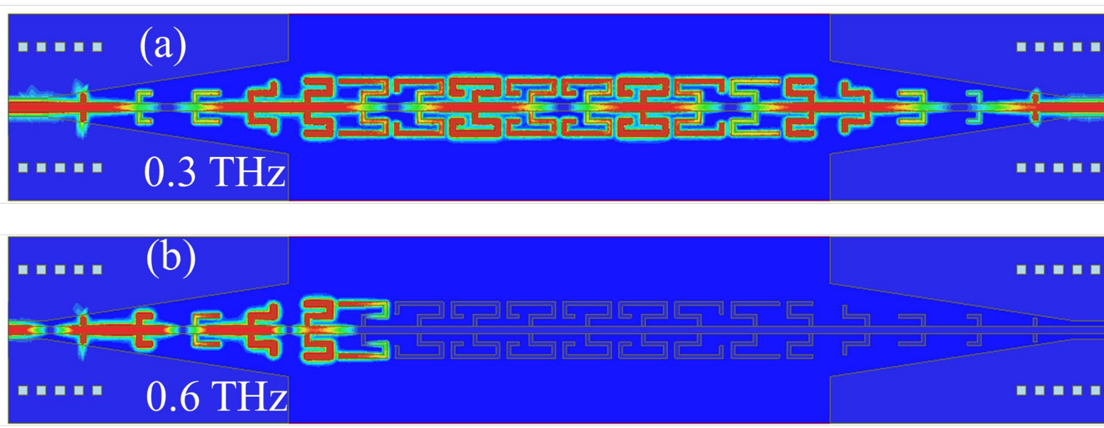

Fig. 6 Simulated electric field distributions of the proposed terahertz on-chip transmission line based on SSPPs. (a) 0.3 *THz*. (b) 0.6 *THz*.

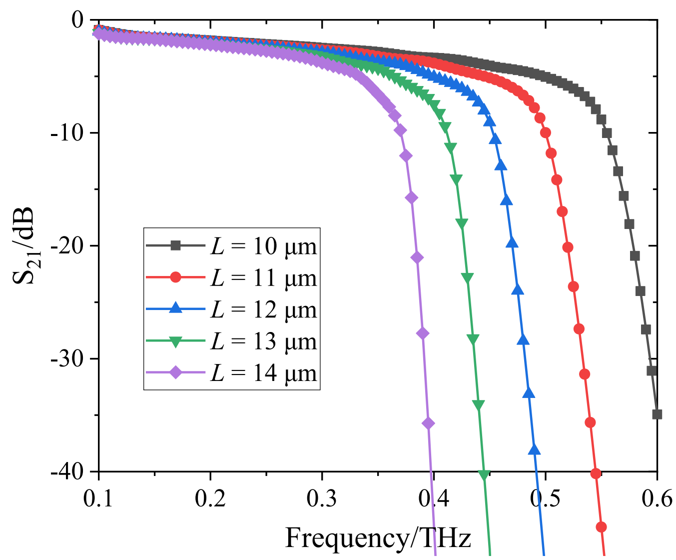

Fig. 7 Simulated insertion loss S_{21} of the folded structure SSPPs transmission line under the different lengths of the folded line L.

Eventually, the insertion loss S21 of the folded structure SSPPs transmission line under the different lengths of the folded line L is simulated to verify the adjustment characteristic of the SSPPs. The simulated results are depicted in Fig. 7, it is obvious that the cut-off frequency of the SSPPs transmission line is determined by the length L, i.e., as the value of L increases gradually, the cut-off frequency will be red-shifted.

3. Conclusions

In this paper, a compact and miniaturized terahertz on-chip SSPPs transmission line is designed based on InP semiconductor technology. Compared with the conventional groove structure SSPPs under the same asymptotic frequency, the footprint of the proposed folded SSPPs is reduced by 70.2%. GCPW is utilized as the feeding port of the SSPPs transmission line, and a gradient transition is used to achieve the mode conversion and impedance matching between GCPW and SSPPs. The proposed terahertz SSPPs transmission line has the advantages of compact structure, convenient design, and has potential application in the terahertz plasmonic semiconductor integrated circuits.

References

[1] Urteaga M, Griffith Z, Seo M, et al. "HBT technologies for THz integrated circuits [J]". *Proceedings of IEEE*, 105(6): 1051–1067(2017).

[2] Moghadami S, Hajilou F, Agrawal P, et al. "A 210 *GHz* fully-integrated OOK transceiver for short-range wireless chip-to-chip communication in 40 nm CMOS technology [J]". *IEEE Transactions on Terahertz Science and Technology*, 5(5): 737–741(2015).

[3]Kim J, Jeon S, Kim M, et al. "H-band power amplifier integrated circuits using 250-nm InP HBT technology [J]". *IEEE Transactions on Terahertz Science and Technology*, 5(2): 215–222(2015).

[4] Radisic V, Leong K, Sarkozy S, et al. "Power amplification at 0.65 THz using InP HEMTs". *IEEE Transactions on Microwave Science and Technology*, 60(3): 724–729(2012).

[5] Zhang H C, He P H, Niu L Y, et al. "Spoof Plasmonic Metamaterials[J]". *Acta Optica Sinica*, 41(1): 0124001 (2021).

[6] Liu P K, and Huang T J. "Terahertz surface plasmon polaritons and their applications [J]". *Journal of Infrared and Millimeter Waves*, 39(2): 169(2020).

[7] Ren Y, Zhang J J, Gao X X, et al. "Active spoof plasmonics: from design to applications[J]". *Journal of Physics: Condensed Matter*, 34:053002(2022).

[8] Liu X Y, Feng Y J, Zhu B, et al. "High-order modes of spoof surface plasmonic wave transmission on thin metal film structure[J]". *Optics express*, Vol.21 (25), p.31155-31165(2013).

[9] Yang L, Jiang S L, Sun G B, et at. "Plasmonic Enhanced Near-Infrared Absorption of Metal-Silicon Composite Microstructure[J]". *Acta Optica Sinica*, 40(21): 2124003(in chinese) (2020)

[10] Wu M, Liang X Y, Sun D X, et al. "Design of Asymmetric Rectangular Ring Resonance Cavity Electrically Adjustable Filter Based on Surface Plasmon Polaritons[J]". *Acta Optica Sinica*, 40(14): 1423001(in chinese) (2020).

[11] Yang H Y, Chen L P, Xiao G L, et al. "MIM Tunable Plasmonic Filter Embedded with Symmetrical Sector Metal Resonator[J]". *Acta Optica Sinica*, 40(11): 1124001(in chinese) (2020).

[12] Luo X, Zou X H, Wen K H, et al. "Narrow-Band Filter of Surface Plasmon Based on Dual-Section Metal-Insulator-Metal Structure[J]". *Acta Optica Sinica*, 33(11): 1123003(in chinese) (2013).

[13] Pendry J B, Martín-Moreno L, and Garcia-Vidal F J. "Mimicking surface plasmons with structured surfaces[J]". *Science*, 305(5685): 847-848(2004).

[14] Garcia-Vidal F J, Martín-Moreno L, and Pendry J B. "Surfaces with holes in them: New plasmonic metamaterials[J]". *Journal of Optics A: Pure and Applied Optics*, 7 (2): S97-S101(2005).

[15] Maier S A, Andrews S R, Martin-Moreno L, et al. "Terahertz surface plasmon-polariton propagation and focusing on periodically corrugated metal wires[J]". *Physics Review Letter*. 97: 176805(2006).

[16] Mart´ın-Cano D, Nesterov M L, Fernandez-Dominguez A I, et al. "Domino plasmons for subwavelength terahertz circuitry[J]". *Optics Express*, 18: 754–764(2010).

[17] Shen, X P, Cui T J, Martin-Cano D, et al. "Conformal surface plasmons propagating on ultrathin and flexible films[J]". *Proceedings of the National Academy of Sciences - PNAS*, 110 (1)：40-45(2013).

[18] Ma H F, Shen X P, Cheng Q, et al. "Broadband and high-efficiency conversion from guided waves to spoof surface plasmon polaritons[J]". *Laser & photonics reviews*, 8 (1)：146-151(2014).

[19] Ye L F, Zhang W, Ofori-Okai B K, et al. "Super subwavelength guiding and rejecting of terahertz spoof SPPs enabled by planar plasmonic waveguides and notch filters based on spiral-shaped units[J]". *Journal of lightwave technology*, 36 (20)：4988-4994(2018).

[20] Bai Y k, Chai B, and Zheng H X. "A Wide-band Leaky-Wave Antenna based on Spoof Surface Plasmon Polaritons[J]". *Study On Optical Communications*, 47(5): 67(2021).

[21] Guo Y J, Xu K D, Deng X J, et al. "Millimeterwave on-chip bandpass filter based on spoof surface plasmon polaritons[J]". *IEEE electron device letters*, 41 (8)：1165-1168(2020).

[22] Zhang H C. "Fundamental Theory, Device Synthesis and System Integration of Spoof Surface Plasmon Polaritons[D]". Nanjing: Southeast University (2020).

[23] Ye L F, Chen Y, Wang Z, et al. "Compact Spoof Surface Plasmon Polariton Waveguides and Notch Filters Based on Meander-Strip Units [J]". *IEEE Photonics Technology Letters*, 33(3): 135-138(2021).

[24] Aziz A, Fan Y, He P, et al. "Spoof Surface Plasmon Polariton Beam Splitters Integrated with Broadband Rejection Filtering Function [J]". *Journal of Physics. D, Applied Physics*, 54(33): 335105(2021).

[25] Zhu D W, Zeng R M, Tang Z T, et al. "Design of Multiband Filter Based on Spoof Surface Plasmon Polaritons[J]". *Laser & Optoelectronics Progress*, 57(17): 172401(in chinese) (2020).

[26] Zhao J, Wang J X, Qiu W B, et al. "Surface Plasmonic Polariton Band-Stop Filters Based on Graphene[J]". *Laser & Optoelectronics Progress*, 55(1): 012401(in chinese) (2018).

[27] Behnam M, Mahdi H M, and Rashid M. "Miniaturized Spoof SPPs Filter Based on Multiple Resonators or 5G Applications [J]". *Scientific Reports*, 11(1): 22557(2021).

[28] Zhang L Q, and Chan C H. "Spoof Surface Plasmon Polariton Filter With Reconfigurable Dual and Non-Linear Notched Characteristics [J]". *IEEE Transactions on Circuits and Systems. II, Express Briefs*, 68(8): 2815-819 (2021).