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High-Efficiency Miniaturized Spoof Plasmonic Waveguide Filter from Direct Current to Millimeter-Wave Frequency

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Spoof surface plasmon polaritons (SSPPs) are highly confined electromagnetic (EM) surface waves in microwave and millimeter-wave frequencies, mimicking the surface plasmon polaritons (SPPs) in the optical frequency, which have many potential applications in plasmonic integrated circuits and systems. Herein, a miniaturized ultrathin SSPP structure is proposed by etching specially designed periodic elements on the coplanar waveguide (CPW), which has been successfully used to realize SSPP waveguide filters with high-efficiency transmissions from the direct current to millimeter-wave frequency region. By changing the dimensions of the SSPP structure, the cutoff frequency of the proposed plasmonic waveguide filter can be tuned from microwave to millimeter-wave frequencies, maintaining the high transmission efficiency in the operating bandwidth. The physical mechanism is explained by the dispersion curves and field distributions. Experimental verification is conducted, which has good agreement with numerical simulations, indicating that the proposed plasmonic waveguide filter can help miniaturize the SSPP components and improve their integration with other devices in ultrawide frequency bands.

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1. Introduction

Surface plasmon polaritons (SPPs) are electromagnetic (EM) waves in optional frequency region, which propagate parallel to the interface between metals and air or metals and dielectrics. However, when the frequency involved is reduced to microwave and millimeter-wave bands, the characteristics of SPPs will disappear and the metals behave like conductors. Through etching periodic grooves or holes on the metal, EM waves can be highly confined on spoof SPPs (SSPPs) structures, which have a similar dispersion characteristic to SPPs. The physical characteristics of SSPPs can be simply controlled by the geometrical parameters of array elements, which have many potential applications in plasmonic applications.[1–4]

Recently, many researches on SSPPs have been conducted in microwave and millimeter-wave frequencies, in which some designs were provided to manipulate the SSPP propagations. Several promising SSPP devices have been developed, such as plasmonic waveguide filters, antennas, beam splitters, and amplifiers.[5–28] As the vital status in integrated circuits and devices in the microwave or millimeter-wave regimes, the plasmonic waveguide filters demand many unique characteristics including the miniaturization and high efficiency. However, as reported in the existing literatures, most SSPP devices are mainly composed of two components: the plasmonic waveguide and the mode conversion part from the spatial mode to SSPP mode,[18–21] which restrict the miniaturization of the SSPP devices.

Accordingly, in order to compact the structures of designs, a series of SSPP-based waveguide filters based on the traditional coplanar waveguide (CPW) have been proposed.[13,14,22,23] Especially, a quasi-SSPP structure based on CPW with only one H-shaped transmission element was investigated, which not only removes the mode conversion part, but also has only one element, extremely minimizing the dimensions of the waveguide.[22] Moreover, a compact transition structure designed with a combination of two inclined rectangular strips and two right-angled triangles was also proposed to reduce the structure size and increase the transmission efficiency of low-pass filter.[26] The insertion loss of the filter at the central frequency of 6.5 GHz is only 0.33 dB. However, the proposed SSPP devices can only be applied in the microwave regime. Therefore, the planar terahertz plasmonic SSPP waveguide filters based on coplanar stripline (CPS) were proposed for the first time.[27] But this concept was only validated in the microwave frequency by experiments, and the smallest insertion loss is 2.2 dB from 3 to 13.1 GHz. Although these efforts have achieved much progress in compacting the structure or improving the transmission efficiency, there is still very limited works on compact SSPP waveguide filters that can realize low insertion loss from the direct current (DC) to millimeter-wave frequencies.

In this work, we proposed a miniaturized and ultrathin plasmonic waveguide filter developed from CPW using special periodic elements to achieve the high transmission efficiency from DC to the millimeter-wave frequencies. The cutoff frequency of proposed plasmonic waveguide filter can vary from microwave to millimeter-wave frequencies by controlling the corresponding parameters. The physical characteristics of proposed structure are analyzed by the dispersion curves and electric field distributions in detail via CST simulation. Additionally, a prototype of the proposed plasmonic waveguide filter is fabricated and measured to verify our concept, which have made a promising for future integrated circuit applications. The proposed plasmonic waveguide filter has the following features: 1) the filter has an ultrawide low-pass bandwidth; 2) the filter has high transmission efficiency within ultrawide bandwidth; 3) the filter has a compact size; and 4) the operating frequency of low-pass filter can be easily designed from microwave to millimeter-wave frequency region by changing corresponding parameters.

2. Basic Unit Cell and Dispersion Characteristics of the Proposed Plasmonic Waveguide Filter

In this section, we start to study the SSPP propagation characteristics by analyzing the unit cell of the proposed plasmonic waveguide filter. The dispersion curves are implemented by the numerical eigen-mode simulation with the commercial CST software. In the CST Microwave Studio, the proposed unit cell is placed in an air box, which is surrounded by periodic and perfectly electrical conductor (PEC) boundaries. Specifically, the boundaries in the propagating direction are periodic and the other boundaries are set as PECs. Moreover, the phase difference between two periodic boundaries varies from 0° to 180°. Thus, the dispersion curves of the fundamental mode can be acquired. The basic unit cell of the proposed SSPP waveguide filter is sketched in **Figure 1**a, which is a common CPW line whose middle stripline is etched with special periodic element. The special periodic element consists of an ellipse splitting in half integrated with a rectangular. The minor axis and the major axis of the ellipse are noted as a and b, respectively. Figure 1b shows the dispersion curves for the proposed plasmonic waveguide filter; it is apparent that the fundamental SSPP mode (mode 1) significantly deviates from the CPW line (black), meaning that the special periodic element makes the unit cell have dispersion characteristic at millimeter-wave frequency. Additionally, the fundamental SSPP mode (mode 1) is located on the slow wave region, which is propagation mode and can support the waves to propagate on the proposed plasmonic waveguide filter. The high-order modes also present in Figure 1b; it can be seen that the high-order modes move to fast wave region gradually, which are radiation modes. Based on these dispersion curves, we can find that the fundamental SSPP mode (mode 1) is the main operation mode for the proposed plasmonic waveguide filter.

3. Electric Field Analysis of the Proposed Plasmonic Waveguide Filter

The propagation property of the proposed plasmonic waveguide filter at millimeter-wave frequency is further analyzed by the simulated electric field distributions on the *x*–*y* plane, as shown in **Figure 2**a. Here, we choose a representative frequency (the cutoff frequency is 94 GHz) for analysis. From Figure 2a, we can see that the electric fields can propagate below the cutoff frequency (50 GHz) with almost no loss and the fields decay quickly above the cutoff frequency (100 GHz) along the *x*-direction, which means that the SSPP waves cannot propagate above the cutoff frequency on the surface. Hence, the SSPP waveguide is also a low-pass filter. Moreover, the magnitudes of energy flow on the cross sections for this model are shown in Figure 2b. It is clearly seen that the electromagnetic fields are highly localized on the adjacent CPW lines and adjacent unit cells, and the fields are confined in the deep subwavelength scale around the waveguide with a majority of energy flow limited in 0.022λ at 50 GHz.

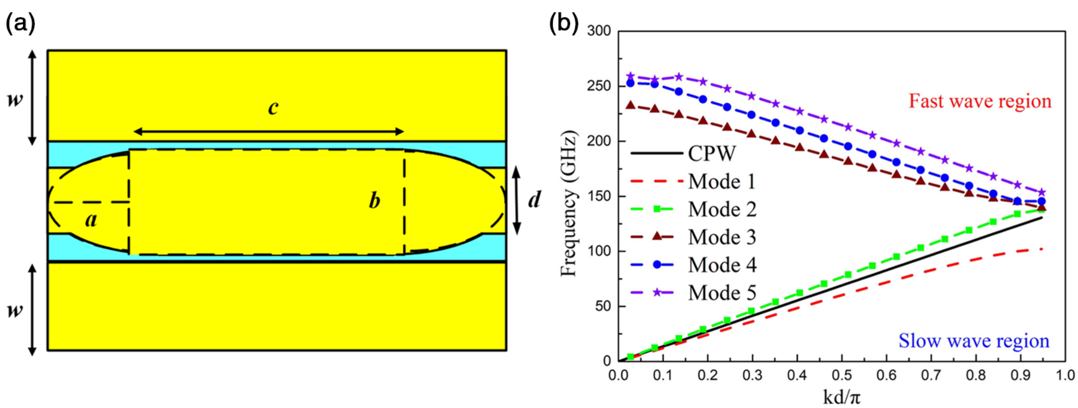

Figure 1. Basic unit cell of the proposed plasmonic waveguide filter under study. a) The basic unit cell. b) Dispersion curves of plasmonic waveguide filter.

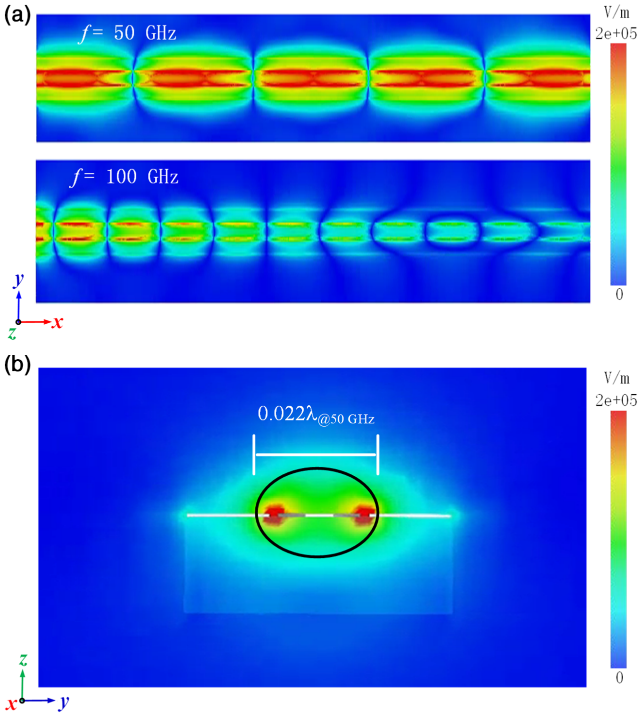

Figure 2. Electric field analysis of the proposed plasmonic waveguide filter. a) Electric field distribution on the *x*–*y* plane. b) The magnitudes of energy flows on cross section.

Therefore, the proposed plasmonic waveguide filter based on the CPW can propagate the SSPP waves and confine the energy tightly at the millimeter-wave frequency.

4. Simulated Results of the Proposed Plasmonic Waveguide Filter

The whole structure of the proposed plasmonic waveguide filter based on CPW is sketched in **Figure 3**a, which is a common CPW line whose middle stripline is etched with the specially designed periodic elements. The SSPP waveguide has two parts: one is the CPW feeding part with the impedance of 50 Ω (part I), and the other is the cascaded unit cell array (part II). The simulated S-parameters of the plasmonic waveguide filter are presented in Figure 3b. It is clearly seen that the proposed SSPP waveguide filter has high transmission efficiency below the cutoff frequency of 94 GHz. The insertion loss is less than 2 dB within 93.25 GHz and the return loss is better than 15 dB within 87.5 GHz. The dimension of the proposed plasmonic waveguide filter is $a = 400$ µum, $b = 90$ µm, $c = 80$ µm, $d = 30$ µm, $l = 110$ µm, $g = 10$ µm, and $w = 90$ µm.

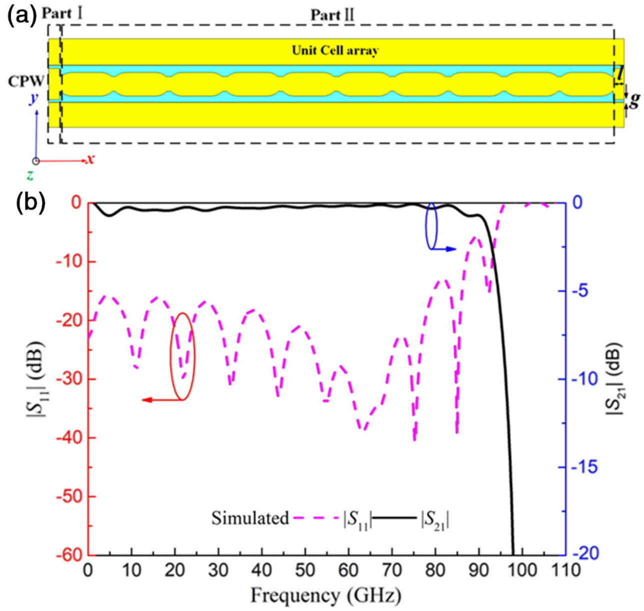

Figure 3. Basic structure and S-parameters of the proposed plasmonic waveguide filter. a) The whole geometry. b) The simulated S-parameters.

5. Experiments and Performance Comparison for Plasmonic Waveguide Filter

The experimental verifications of the proposed plasmonic waveguide filter are conducted to prove the simulated results. In order to validate the correctness of the simulated results of our proposed design, a prototype of the plasmonic waveguide filter whose operating frequency is below 94 GHz is fabricated and measured. The proposed plasmonic waveguide filter (cutoff frequency is 94 GHz; see **Figure 4**c) is fabricated on the 127 µm quartz substrate with $\varepsilon_r = 3.75$ and the loss tangent $\tan(\delta) = 0.0004$. The metallic strips have a thickness of 4 µm. This model has the following design parameters: $a = 400$ µm, $b = 90$ µm, $c = 80$ µm, $d = 30$ µm, $l = 110$ µm, $g = 10$ µm, and $w = 90$ µm. It is noteworthy that in this study we fabricate the filter array to facilitate measuring. We also fabricated the standard CPW lines on the prototype for calibration (see Figure 4a). The fabricated standard CPW model has 90 µm metal width and width of the slot line is 10 µm. Figure 4b gives the measurement environment of the proposed plasmonic waveguide filter. The measured results have good agreements with the simulated ones, as shown in Figure 4c, demonstrating that the proposed SSPP waveguide filters can achieve high-efficiency transmissions from DC to millimeter-wave frequencies by changing the corresponding parameters. It should be noted that due to the limitation of the measurement environment, the measured frequency for the proposed design can only start from 50 GHz to higher frequencies.

In order to compare the performance of the proposed designs with other existing filters, previous studies[29–33] introduce the filters based on the substrate integrated waveguide (SIW), deep reactive ion etching (DRIE), through-silicon via (TSV), computer numerical control (CNC), and SSPPs technology. **Table 1** summarizes the performance comparison of existing filters. It is seen that although the SIW and TSV filters have small size, however, the insertion loss still needs to be improved.[29,30,32] Accordingly, based on the DRIE and CNC technology, Zhao et al.[31] and

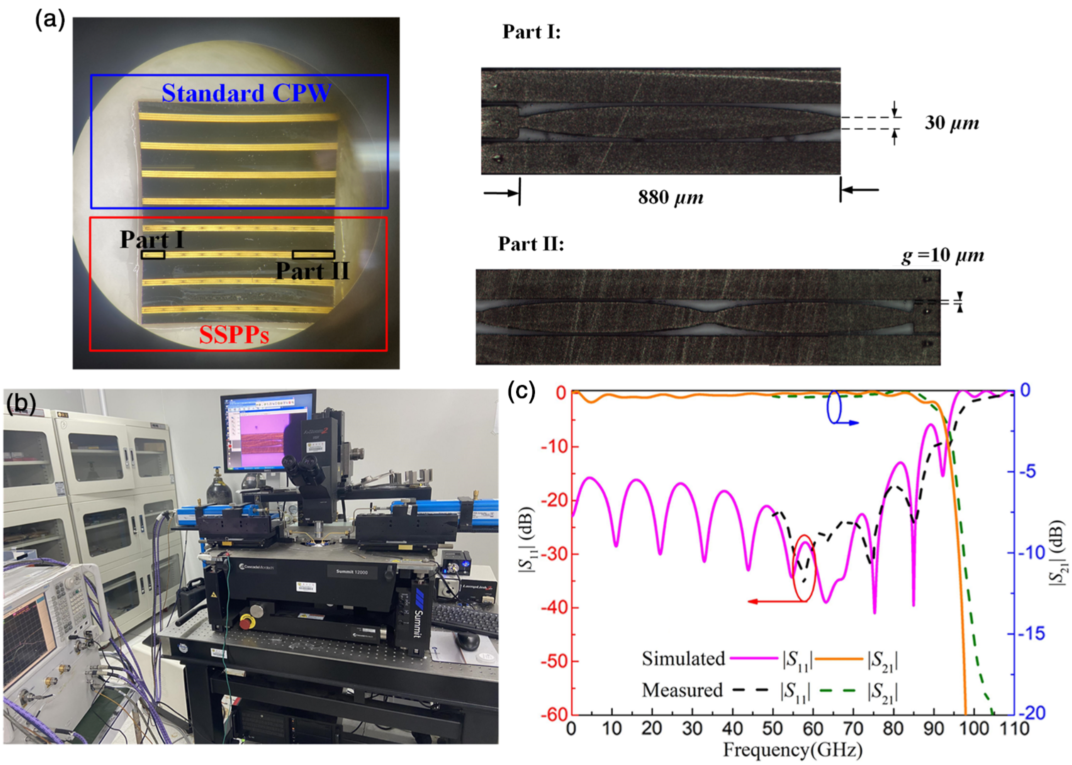

Figure 4. a) Fabrication prototype of the proposed plasmonic waveguide filter. b) Measurement environment of the design. c) The measured S-parameters of the proposed plasmonic waveguide filter.

Table 1. Performance comparison of existing filters.

Ref.[a)]	Platform	f_{op}	Filter size [λ_h]	Insertion loss [dB]	Return loss [dB]
[29]	SIW	131.3–149.6 GHz	0.6 × 0.4	1.91	11
[30]	SIW	128.9–150.4 GHz	0.9 × 0.39	2.44	11
[31]	DRIE	132–148 GHz	0.82 × 0.41	0.61	–
[32]	TSV	260–400 GHz	0.9 × 0.28	1.5	15
[33]	CNC	132–149 GHz	–	0.52	18.9
[34]	SSPPs	0–1 THz	–	2.6 @ (500 GHz)	11
This work	CPW (SSPPs)	0–94.95 GHz	0.09 × 0.04	<2 @ (0–93.25 GHz)	>15 @ (0–87.5 GHz)

[a)] f_{op} is the operating frequency; λ_h is the wavelength at the highest operating frequency.

Xiao et al.[33] proposed low insertion loss filters. However, all of these high-frequency structures were designed for band-pass filter, which were not benefit for low-pass designing. Jaiswal et al.[34] proposed an SSPP low-pass filter with operating bandwidth cover from 0 to 1 THz, which has a relatively wide bandwidth. Nevertheless, its insertion loss is tremendous at high frequency. Therefore, compared to other filters, our proposed plasmonic waveguide filter can be easily designed at millimeter-wave frequency with a relatively good performance with small size. It should be noted that SSPP design is a periodic structure; hence, the comparison table does not give the relevant length data.

6. Conclusion

On our plasmonic waveguide filters, we observe wavelength-scale energy confinement around the slot lines of CPW below the cutoff frequency, presenting the SSPP characteristics across the microwave to millimeter-wave frequencies. We have fabricated and measured a prototype of the proposed plasmonic waveguide filter to verify our design concept, whose operating frequencies cover from DC to 94 GHz. The measured results show that the filter has high transmission efficiencies under cutoff frequency. The measured results have good agreements with numerical simulations. The miniaturization and high-efficiency characteristics of the plasmonic waveguide filter are very promising for the future applications in a variety of microwave and millimeter-wave components, circuits, and systems.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Research data are not shared.

Keywords

coplanar waveguide, direct current, low-pass filter, spoof surface plasmon polaritons

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