(Received 8 February 2026, Accepted 8 April 2026, Scheduled 26 April 2026)

Miniaturization and Transition Sharpening of Plasmonic Filters via Interdigital Capacitors

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ABSTRACT: This paper proposes a spoof surface plasmon polariton (SSPP) based on a coplanar waveguide (CPW) with an interdigital structure, aiming to realize a plasmonic filter with both miniaturization and sharp transition characteristics. Dispersion and transition analyses demonstrate that the proposed unit exhibits flexibly controllable dispersion and transition features by tuning the geometrical parameters of the interdigital unit. Based on this, a compact filter with the proposed structure was designed, simulated, and experimentally validated. The introduction of the interdigital slot structure provides an additional degree of freedom for tuning, enabling the filter to achieve a steep transition from the passband to the stopband (with a roll-off rate of up to 181.31 dB/GHz) while maintaining a compact size. The measured results are in good agreement with the simulated ones, which verifies the effectiveness of the proposed design. In addition, the bandpass response introduced by higher-order modes offers a feasible route toward the multimode and multifunction integration of filters.

1. INTRODUCTION

Surface electromagnetic waves supported by periodically textured metallic structures, commonly referred to as spoof surface plasmon polaritons (SSPPs), have attracted sustained interest in the microwave and terahertz regimes owing to their controllable dispersion characteristics [1, 2]. Unlike conventional transmission lines, SSPP waveguides exhibit strong field confinement and slow-wave behavior, which naturally introduce frequency-selective responses that resemble filtering features [3, 4].

As a planar transmission line, the coplanar waveguide (CPW) features signal and ground planes on the same layer, offering advantages, including low dispersion, ease of integration, and convenience for integrating lumped elements or planar structures [5]. From a physical mechanism perspective, after periodically etching slot lines on the CPW ground plane, the localized resonant modes supported by the slot lines will couple with the SSPP transmission modes, thereby effectively exciting the SSPP mode and achieving a low-pass response [5–9]. This coupling process can be regarded as a generalized mode "hybridization" effect [10], whose spectral characteristics can be described by the local resonance theory [11]. Such a CPW-based SSPP structure not only overcomes the limitation of conventional SSPP that requires increased transverse dimensions due to complex mode conversion, but also exhibits lower radiation loss [12]. In this composite structure, the properties of the localized modes and their coupling strength to the main transmission line can be systematically tuned by adjusting geometric parameters, thereby controlling the cutoff frequency of the dispersion [13] and providing more degrees of freedom for regulating the filtering performance.

Accordingly, the research on CPW-SSPP-based filters has advanced. In [12], by loading capacitors, two types of CPW-SSPP structures were designed, achieving transverse width reductions of 64% and 76%, respectively. In [14], semi-circular unit structures were etched on both sides of a CPW center line. Furthermore, based on an equivalent circuit model analysis, the fabricated filter exhibited an out-of-band rejection greater than 43 dB and a peak insertion loss as low as 1.1 dB. Based on butterfly-shaped structures, the low-pass filter (LPF) proposed in [15] realized a 33% reduction in the cutoff frequency compared with conventional rectangular designs.

However, a steep transition from the passband to the stopband in filters is critical for effectively suppressing signal aliasing and enhancing the anti-interference robustness of the system [16]. In conventional filter design, a common approach to achieve a steeper transition is to increase the filter order [17, 18], which, however, inevitably enlarges the circuit footprint and increases insertion loss. Alternatively, transmission zeros can be introduced by incorporating resonant elements or hybrid guided-wave structures to enhance stopband rejection [19–22], but these techniques often come at the cost of increased device size or fabrication complexity. While the existing CPW-SSPP filter studies mentioned above have made remarkable progress in miniaturization, low insertion loss, and wideband suppression, little attention has been paid to improving the steepness of the transition band.

Motivated by this limitation, this study proposes a novel SSPP unit with an interdigital slot structure on the bottom strip, which is developed from [8]. With the introduction of inter-

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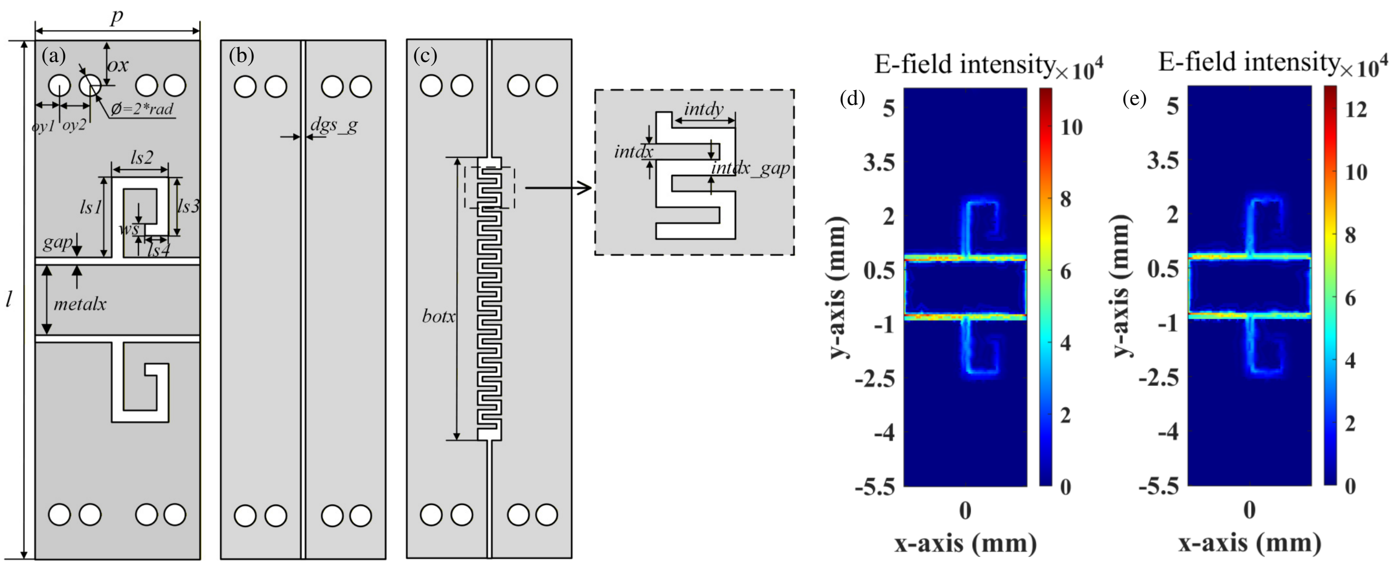

FIGURE 1. Layouts and simulated electric field distributions of the SSPP unit cells. (a) Top view of both the conventional and the proposed unit. (b) Bottom view of the conventional unit. (c) Bottom view of the proposed unit. (d) Field distributions of the traditional unit. (e) Field distributions of the proposed unit.

TABLE 1. SSPP unit cell parameters (Unit: mm).

Parameter	*p*	*l*	*ls1*	*ls2*	*ls3*	*ls4*	*ws*	*metalx*	*ox*
Value	10/3	11	2/1.2	1.45/1.2	1.25	0.5	0.25	1.5	0.95
Parameter	*dgs_g*	*botx*	*intdx*	*intdy*	*intdx_gap*	*rad*	*oy1*	*oy2*	
Value	0.1	6	0.1	0.4	0.1	0.2	0.525	0.6167	

digital fingers, the proposed structure can effectively modulate the dispersion characteristics and asymptotic frequency. Notably, the designed unit features a compact size while achieving a sharp transition. Based on this design, an SSPP filter was fabricated and characterized. Measured S-parameters demonstrate that the proposed filter achieves a roll-off rate (ROR) of 181.31 dB/GHz, validating the effectiveness of the proposed design. Furthermore, the bandpass response originating from the higher-order modes of the proposed filter enables the potential for multimode propagation and multifunction integration in filter designs, providing new insights into future filter research.

2. THEORY AND DESIGNING PRINCIPLE

Figure 1 illustrates the proposed SSPP unit cell. Developed from the conventional coplanar waveguide (CPW) SSPP reported in [8], the proposed unit consists of a central metallic strip flanked by two symmetric groove-etched ground planes. However, unlike the original structure, an interdigital slot is patterned on the bottom ground conductor, with finger length *intdy*, finger width *intdx*, and coupling gap *intdx_gap*. Other associated geometrical dimensions are defined as follows: the width of the central conductor is denoted as *metalx*, and the gap between the conductor and the lateral ground is denoted as *gap*. Each spiral-shaped groove has a line width of *ws*. To effectively suppress radiation loss and construct a continuous, integrated CPW ground plane between the top and bottom layers, two rows of metallic vias with a diameter of rad are introduced for interlayer grounding. The periodicity of the unit cell is p. The substrate of the unit and all other circuits has a thickness of 0.5 mm, dielectric constant of 2.65, and loss tangent of 0.02. All geometrical parameters are given in Table 1.

To assess the electromagnetic field confinement capability, both conventional and proposed unit cells were simulated. Figs. 1(d) and (e) depict the simulated z-component of the electric field on a plane slightly above the top metallization layer. Notably, the high-curvature features of the CPW grooves promote resonance energy concentration, leading to localized electric field enhancement [23]. Meanwhile, the electric field distribution of the proposed unit is highly consistent with that of the conventional counterpart, verifying its ability to sustain the propagation of SSPPs.

The dispersion characteristics of the two unit cells are compared in Fig. 2(a). Both configurations exhibit typical SSPP dispersion: the curve follows the light line at low frequencies and gradually deviates as the frequency increases, eventually saturating at an asymptotic frequency, which is a signature of strong subwavelength confinement. Notably, the proposed SSPP unit cell with an interdigital slot saturates at a lower asymptotic frequency than the conventional one because the same degree of mode confinement can be maintained with a reduced period.

Figure 2(b) compares the simulated transmission characteristics of the two SSPP units. Both designs produce a low-pass

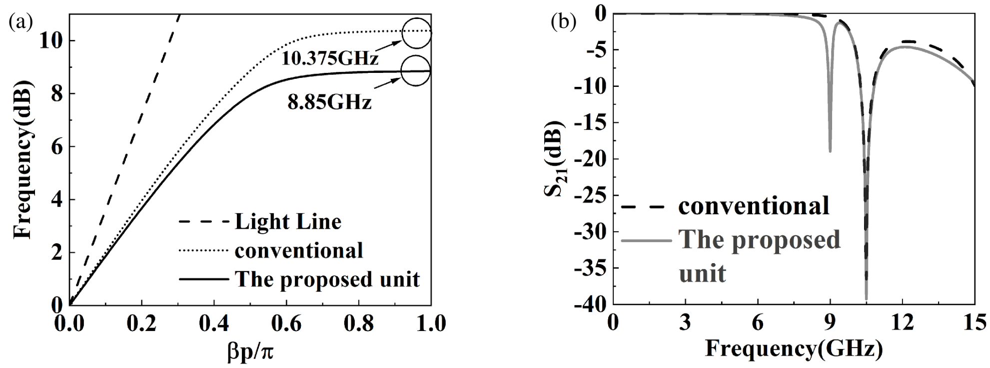

FIGURE 2. Dispersion and transmission performance comparison of conventional and proposed SSPP unit cells. (a) Dispersion curves. (b) Simulated transmission coefficient $|S_{21}|$.

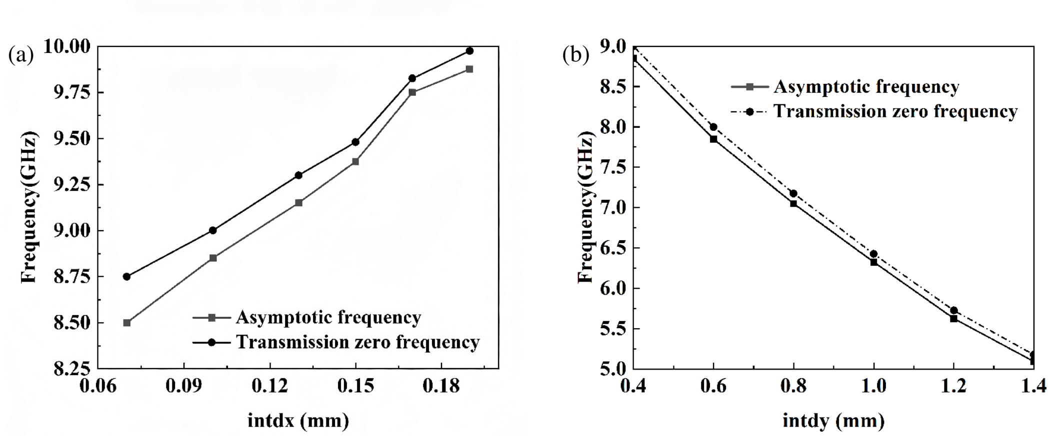

FIGURE 3. Influence of interdigital-slot dimensions on the dispersion and transmission characteristics. (a) Finger length (*intdx*). (b) Finger width (*intdy*).

filtering response with transmission zeros to sharpen the transition, thus enabling both SSPP units to construct high-selectivity plasmonic filters. In particular, in contrast to the conventional unit, the proposed unit with an interdigital slot introduces two transmission zeros at 9.0 GHz and 10.5 GHz, and the primary transmission zero is much closer to the asymptotic frequency. This feature yields a markedly sharper roll-off at the passband edge, making the proposed SSPP unit superior to the conventional one in improving the selectivity of plasmonic filters.

To further elucidate the influence of the integrated interdigital structure on the selectivity of the plasmonic filters, Fig. 3 depicts the simulated cutoff frequency and transmission zero frequency of the proposed unit for different geometric dimensions of the interdigital structure.

In Fig. 3(a), *intdx* is swept from 0.07 mm to 0.19 mm in 0.02 mm steps while all other geometrical parameters are held constant. Fig. 3(b) shows the effect of finger length *intdy*, which is varied from 0.5 to 1.9 mm in increments of 0.2 mm. The results show that both the cutoff frequency and the transmission zero frequency increase with increasing *intdx* and decrease with increasing *intdy*, confirming that the dispersion characteristics can be finely tuned by adjusting the dimensions of the interdigital structure. Similarly, increasing either *intdx* or *intdy* pulls the transmission zero closer to the passband-stopband transition.

More importantly, both geometrical parameters control the location of the transmission zero. Enlarging *intdx* or *intdy* consistently shifts the transmission zero toward the asymptotic frequency, thereby improving the steepness of the filter's roll-off. Therefore, the geometrical parameters of the interdigital structure offer a powerful tuning mechanism, allowing the overall response of the plasmonic filter stopband edge to be controlled by modifying the local geometry.

From the above comprehensive analyses, the incorporation of the interdigital structures exerts dual effects on the dispersion and transition characteristics of the SSPP structure, thereby providing a feasible design approach to tailor such key performance characteristics for the rational design of SSPP-based devices.

3. DESIGN AND MEASUREMENT

Based on the interdigital structures and dispersion analysis, a compact SSPP filter with a steep transition was designed. The filter in Fig. 4 comprises three functional regions: Part I serves as the input/output port implemented in the CPW; Part II acts as a transition zone between the CPW and SSPP sections, functioning as both a mode converter and an impedance transformer to ensure stable signal transmission; and Part III consists of five periodic interdigital-SSPP unit cells. Figs. 4(a) and (b) show

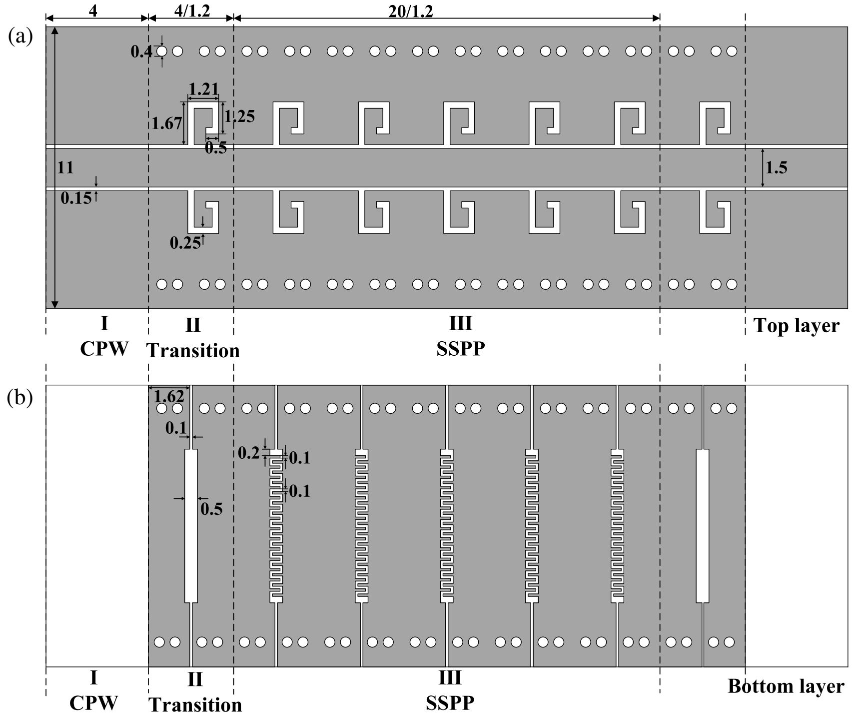

FIGURE 4. Layout of the proposed SSPP filter: (a) Top view, (b) bottom view (Unit: mm).

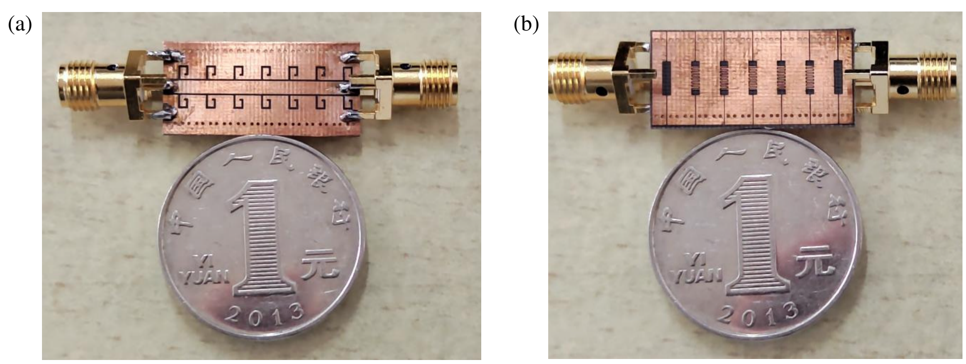

FIGURE 5. Photograph of the fabricated prototype: (a) Top view, (b) bottom view.

the schematic configurations of the front and back sides of the designed filter, respectively.

To validate the proposed design, experimental characterization was performed using a vector network analyzer (N5222A, Keysight) over the frequency range of 0–18 GHz. The fabricated prototype of the proposed SSPP filter is presented in Fig. 5, with its top and bottom views shown in Figs. 5(a) and (b), respectively. Fig. 6 presents a comparison of its simulated and measured S-parameters. It can be clearly observed that the measured results are in excellent agreement with the simulations. The S_{11} remains below -10 dB over the frequency band from 0 to 8.494 GHz, indicating good impedance matching in the passband. The roll-off rate (ROR) corresponding to S_{21} from -3 dB to -20 dB is 181.31 dB/GHz, which fully validates the significant advantage of this structure in achieving a sharp transition.

Notably, due to the interdigital structure integrated on the bottom layer, a small notch can be observed in both the simulated and measured S_{21} curves in the enlarged view after the transmission zero frequency of 8.8 GHz. This feature is in good agreement with the simulated notch near 9 GHz shown in Fig. 2(b). The slight discrepancies between simulation and measurement are mainly attributed to PCB fabrication tolerances, assembly imperfections, and the influence of the measurement environment. Additionally, as can be seen from Fig. 6, the proposed filter actually exhibits dual-mode transmission characteristics: a low-pass response from 0 to 8.494 GHz and a high-pass transmission band from 11.5 GHz to 13 GHz induced by the higher-order modes of SSPP. This provides a new solution for future multiband and multifunctional integrated SSPP devices.

Table 2 compares the proposed SSPP filter with some reported SSPP filters in terms of asymptotic frequency f_c, roll-off

TABLE 2. Comparison of the proposed filter with other works.

Refs.	f_c (GHz)	ROR (dB/GHz)	IL (dB)	RL (dB)	Physical size (mm)
[6]	1.67	106.25	4	10	70×20.8
[7]	2.5	-	-	13.1	120×50
[15]	10	-	< 1.6	> 13.6	83×22
[17]	5.53	105	0.8	> 14	26.3×8.416
[20]	1.44	90.24	0.2	14	12×11
[21]	1.26	103.9	0.3	12	26.5×17.17
[22]	6.77	-	0.27	10	61×10
This work	8.494	181.31	< 0.1	> 17.9	31.3×11

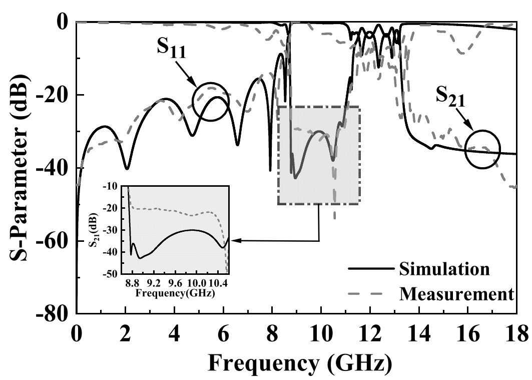

FIGURE 6. Simulated and measured S-parameters of the proposed SSPP filter.

rate (ROR), passband insertion loss (IL), return loss (RL), and physical size. According to the table, the proposed SSPP in this paper has both the sharpest transition and an excellent compact physical size, while also exhibiting superior passband insertion loss performance.

4. CONCLUSION

In this study, a CPW-based SSPP loaded with an interdigital structure on the bottom layer was proposed and experimentally validated. Dispersion characteristic analysis and S-parameter simulation results demonstrate that the proposed configuration offers flexibly controllable dispersion and transition characteristics through the adjustment of geometrical parameters. Based on these findings, a compact filter was designed, fabricated, and measured. Both the simulated and experimental results confirm that the filter achieves simultaneous miniaturization and an ROR of 181.31 dB/GHz. Furthermore, the dual-mode transmission characteristic of the proposed filter provides a new perspective for the future development of multifunctional integrated SSPP devices.

ACKNOWLEDGEMENT

This work was supported in part by the National Natural Science Foundation of China under Grant U22A2004 and in part by the Key Research and Development Program Foundation of Zhejiang under Grant 2024C01060 and Grant 2025C01079.

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