Plasmonics
https://doi.org/10.1007/s11468-024-02318-0

RESEARCH

An Ultra-Compact Surface Plasmon Transmission Line Based on Partially Grounded Coplanar Waveguide

Yu-Xin Cui[1] · Yu-Xuan Zhang[1] · Lin Li[1]

Received: 15 January 2024 / Accepted: 17 April 2024

Abstract
In this article, a new spoof surface plasmon polariton (SSPP) developed from partially grounded coplanar waveguides (PGCPW) is proposed. By utilizing folded-strip-type DGS, the dispersion characteristics can be controlled. Based on the equivalent circuit analyses, it is found that the proposed PGCPW SSPP features lower asymptotic frequency than the conventional grounded coplanar waveguides (GCPW) SSPP with the same size occupation. As a result, the proposed PGCPW SSPP has a smaller size occupation to obtain the same asymptotic frequency. To illustrate the design principle, the proposed PGCPW SSPP TL is designed, fabricated, and tested. Results validate that the proposed PGCPW SSPP TL exhibits smaller unit cell size, transition size, and total size.

Keywords Spoof surface plasmon polariton (SSPP) · Partially grounded coplanar waveguides (PGCPW) · Dispersion curve · Defected ground structure (DGS)

Introduction

Surface plasmon polaritons (SPPs) are a special electromagnetic (EM) wave mode that exists at the interface of two media with opposite dielectric constants [1]. They can propagate along the interface but decay exponentially in the other directions according to Maxwell's equations [2]. They have attracted significant attention in recent years due to their ability to concentrate light in subwavelength structures, which has potential applications in nanophotonics, sensing, and imaging [3]. Although devices and systems based on SPP have great potential, natural SPP cannot continue to propagate in the microwave and terahertz frequency bands due to the fact that metals behave as perfect electrical conductors (PECs) [4].

To address these issues, spoof SPPs (SSPPs) were introduced to simulate the performance of SPPs at microwave and terahertz frequencies [5]. In 2004, Pendry et al. first demonstrated that structured metal surfaces can support SSPPs [6]. However, SSPP devices typically require larger sizes, which to some extent limits the practical application of SSPP. On the one hand, relatively complicated transition structures are required to realize mode-conversion and impedance matching, which increases overall dimensions largely. On the other hand, the larger size of SSPP unit cell with higher asymptotic frequency poses the challenge to the compactness of SSPP devices, too.

In recent years, many new structures and techniques have been proposed to reduce the size of SSPPs. To reduce the size of unit cells, a T-shaped groove is designed in [7] to realize the miniaturization of the proposed filter by decreasing the equivalent cutoff frequency of the SSPPs. In [8], by introducing capacitive loading metal strips, the width of SSPP transmission lines is reduced by half and the field constraints are stricter. However, its mode-conversion structure is still very complex. A surface plasmon transmission line using capacitive loading technology was proposed in [9], which has a much smaller linewidth. A compact folded SSPP TL was used in [10] to reduce the lateral size to nearly 2/5 of the original size. In [11], by combining SSPP with different substrate-integrated waveguides, the lateral width can be reduced to a certain extent.

Additionally, simplifying mode conversion structures to achieve better impedance matching can also promote the size reduction and performance optimization of SSPPs. In

✉ Lin Li
lilin_door@hotmail.com

1 The Key Laboratory of Intelligent Textile and Flexible Interconnection of Zhejiang Province, School of Information Science and Engineering, Zhejiang Sci-Tech University, Hangzhou 310018, China

Published online: 25 April 2024

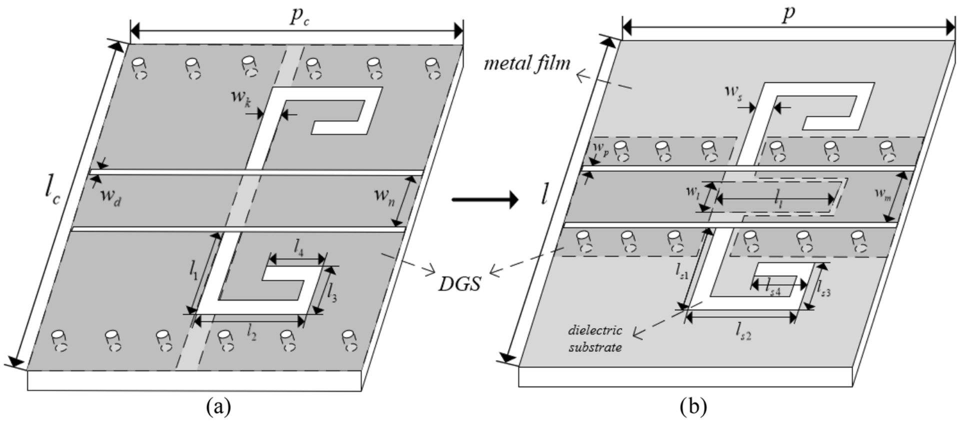


Fig. 1 **a** Conventional SSPP unit cell. **b** Proposed SSPP unit cell

[12], by using gradient corrugated strips with grounding on both sides, a simple and efficient conversion between waveguide and SSPP is achieved. In addition, the defected ground structure (DGS) further enhances the constraints of SSPP, achieving miniaturization of waveguides, too. In [13], a compact transition is built through two matching units and a tapered strip, achieving a simple mode conversion structure. In [14], a deceptive SPP transmission line with zigzag grooves was used to achieve better impedance matching and stronger field constraints. In [15], a new CPW SSPP with a simple and efficient mode conversion structure is initially proposed, and then an improved SSPP using GCPW and DGS is presented. This improved SSPP has both simplified mode conversion structure and unit cell with lower asymptotic frequency. However, transition composed of unit cells with gradient groove lengths is required to obtain impedance matching, which makes the size a little larger.

To overcome the drawbacks of SSPP in [15] and further explore and refine simplified mode conversion structures, in this article, a new SSPP developed from the partially grounded coplanar waveguide (PGCPW) is proposed, which utilizes the folded strip-type DGS. This new PGCPW SSPP has the advantages of lower asymptotic frequency, improved impedance matching, and simple mode-conversion structure, which is beneficial to the size reduction of the SSPP system. The design principle is illustrated, and experimental examples are provided. The results demonstrate the effectiveness of the design strategy based on the proposed PGCPW SSPP.

Theory and Design Principle

Figure 1 shows the proposed SSPP unit cell, where the metal film portion is represented in gray and the dielectric substrate portion is indicated in white. This SSPP unit cell is developed from the conventional GCPW SSPP proposed in [15]. Like the GCPW SSPP unit cell in [15], the proposed SSPP unit cell has a CPW line in the middle of the top layer, and the meandering spiral grooves etched on both sides of the CPW ground. Besides, two rows of metallic vias and a defected ground structure (DGS) are employed in the two SSPP unit cells in Fig. 1. With these extra structures to compose GCPW structure, better signal transmission and prevention of signal interference can be achieved, enhancing the overall performance of the system.

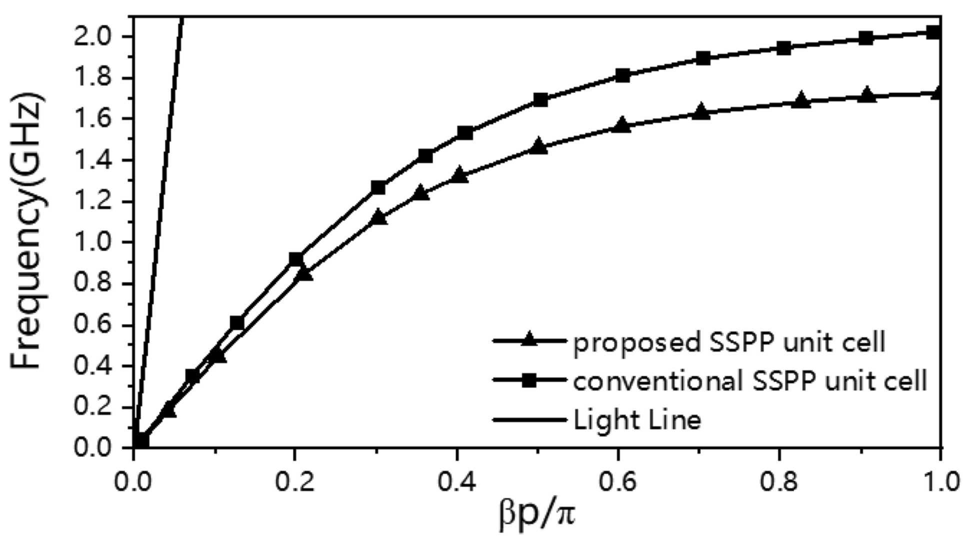


Fig. 2 Comparison of simulated dispersion feature of conventional and proposed SSPP unit cell

Table 1 SSPP Parameters (unit: MM)

Parameter	p_c	l_c	w_d	w_n	w_k	l_1	l_2	l_3	l_4
Value	10	20	0.15	2.2	0.5	5	4.5	3	3.5
Parameter	p	l	w_p	w_m	w_s	l_{s1}	l_{s2}	l_{s3}	l_{s4}
Value	10	20	0.15	2.2	0.5	5	4.5	3	3.5

However, there are two main differences between the proposed SSPP unit cell and the conventional one. Firstly, in terms of the coverage of the bottom ground structure, the ground in Fig. 1a covers all the bottom of the unit cell substrate, while the ground in Fig. 1b only covers the corresponding bottom part under the CPW line. Thus, the proposed SSPP is a partially grounded CPW (PGCPW) SSPP. Secondly, although both unit cells utilize the DGS, the conventional GCPW SSPP unit cell has a strip-type DGS, while the proposed PGCPW SSPP unit cells use a folded strip-type DGS.

Figure 2 compares the simulated dispersion feature of the two different SSPP unit cells. Both unit cells and all the designs in this article are constructed on the dielectric substrate FR4 with a thickness of 0.8 mm, a dielectric constant of 4.4, and a loss tangent of 0.02. All geometric parameters are shown in Table 1. Obviously, the dimensions of the CPW lines, the grooves etched on the top layer of the proposed unit cell are the same as those of the conventional unit cell, except for the DGS structure on the bottom layer.

As shown in Fig. 2, both two SSPPs exhibit obvious SSPP response, which stays close to the light line at low frequencies but goes away at high frequencies. And the proposed PGCPW SSPP unit cell has a lower asymptotic frequency than the conventional GCPW unit cell. Therefore, the proposed PGCPW SSPP unit cell can adopt a smaller size compared to the conventional GCPW SSPP-TL to achieve the same asymptotic frequency.

To gain a deeper insight into the size reduction mechanism of the proposed PGCPW SSPP unit cell, the equivalent circuit model in Fig. 3 is presented to depict both the conventional and proposed SSPP unit cell. In the figure, the CPW lines are represented by the transmission lines, the effect of the slot-type grooves on the CPW ground and the DGS on the bottom ground are represented by the inductors, and the parameters of the equivalent circuit can be extracted from EM simulations of the unit cell. Table 2 compares the extracted parameters of the two SSPP unit cells with the dimension listed in Table 1.

In the equivalent circuit model, the current and voltage are defined as the current flowing through a conductor and the potential difference between the conductor and ground,

Fig. 3 The equivalent circuit model of the unit cell

respectively. For the periodic structures, the relationship between the input (V_n, I_n) and output (V_{n+1}, I_{n+1}) can be calculated, namely the voltage and current of the unit cell. The voltage and current of the unit cell meet the following relationship.

$$V_{n+1} = V_n e^{j\beta p}, I_{n+1} = I_n e^{j\beta p} \tag{1}$$

where β is propagation constant.

The transfer matrix, also known as the *ABCD* matrix, can be used to describe the input–output relationship between adjacent unit cells in a periodic structure.

$$\begin{pmatrix} V_n \\ I_n \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} V_{n+1} \\ I_{n+1} \end{pmatrix} \tag{2}$$

Due to the symmetrical structure proposed in this article, the propagation constant β should satisfy the following relationship:

$$\cos(\beta p) = A \tag{3}$$

By utilizing the circuit parameters of the proposed equivalent circuit model, the ABCD matrix can be calculated as follows:

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} \cos 2\theta - \frac{\omega L \sin 2\theta}{2Z_0} & jZ_0 \sin 2\theta + j\omega L \cos^2\theta \\ \frac{j \sin 2\theta}{Z_0} - \frac{j\omega L \sin^2\theta}{Z_0^2} & \cos 2\theta - \frac{\omega L \sin 2\theta}{2Z_0} \end{pmatrix} \tag{4}$$

where ω is the angular frequency.

By combining Eqs. (3) and (4), the propagation constant β can be obtained as follows:

$$\beta = \frac{1}{p}\cos^{-1}(A) = \frac{1}{p}\cos^{-1}\left[\cos 2\theta - \frac{\omega L \sin 2\theta}{2Z_0}\right] \tag{5}$$

And the asymptotic frequency corresponds to the frequency where $|\beta| = \infty$. Based on the formula presented above, the correlation between the asymptotic frequency f_a and circuit components can be derived as below.

$$f_a = \frac{Z_0 \cot \theta}{\pi L} \tag{6}$$

As seen from Eqs. (5) to (6), the increase of L leads to the decrease of A, resulting a larger β and a lower f_a. And it can be seen from Table 2 that the proposed PGCPW SSPP has a larger inductance than the conventional GCPW SSPP. As a result, just as shown in Fig. 2, the proposed PGCPW SSPP

Table 2 Equivalent circuit parameters

	Z_0	θ	L
Conventional SSPP	38	30	4.1
Proposed SSPP	38	30	6.2

exhibits lower asymptotic frequency and more obvious SSPP response than the conventional GCPW unit cell.

Since the main difference between the two SSPP unit cells is the DGS, the decrease in asymptotic frequency can be attributed to the extra inductance brought by the folded strip-type DGS. To investigate the relationship between the asymptotic frequency and the dimension of the folded strip-type DGS, Fig. 4a, b depicted the equivalent circuit (E.C.) computed and E.M. simulated dispersion curves with different w_l and l_l, respectively.

In Fig. 4a, l_l is set to 4.5 mm, and the values of w_l are 0 mm, 0.3 mm, and 0.6 mm, respectively. Clearly, the case of $w_l = 0$ corresponds to DGS without folded structure. As shown in Fig. 4a, the asymptotic frequency of the proposed PGCPW SSPP unit cell with $w_l = 0.3$ mm, and $w_l = 0.6$ mm is lower than that of the PGCPW SSPP unit cell without folded structure. Moreover, the larger the value of w_l is, the lower the asymptotic frequency is, and the smaller the size of the corresponding structure.

The dispersion curves can also be influenced by the length of the folded structure l_l. Figure 4b compares the

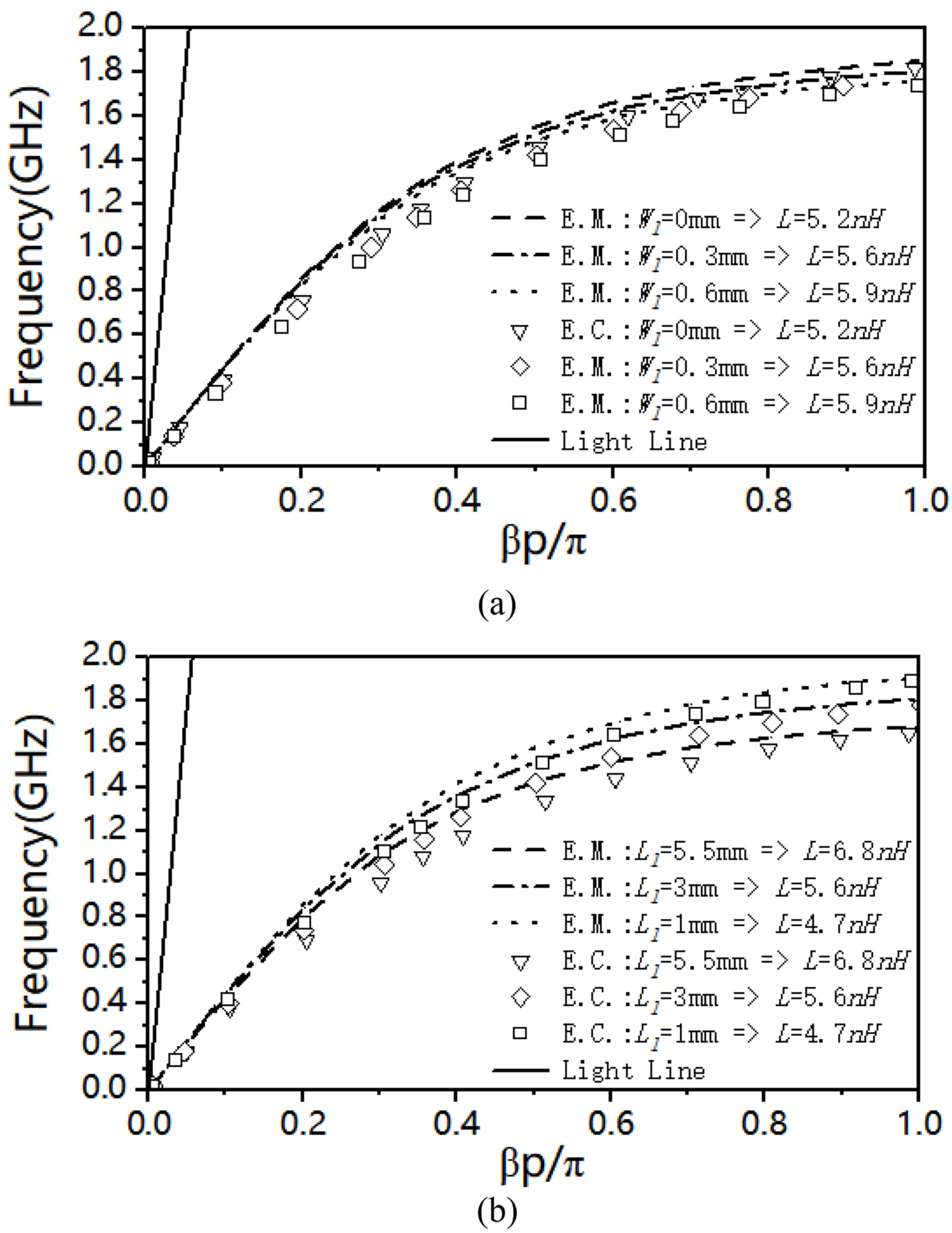


Fig. 4 The E.C. computed and E.M. simulated dispersion curves of the proposed SSPP unit cell. **a** Different w_l and fixed l_l. **b** Different l_l and fixed w_l

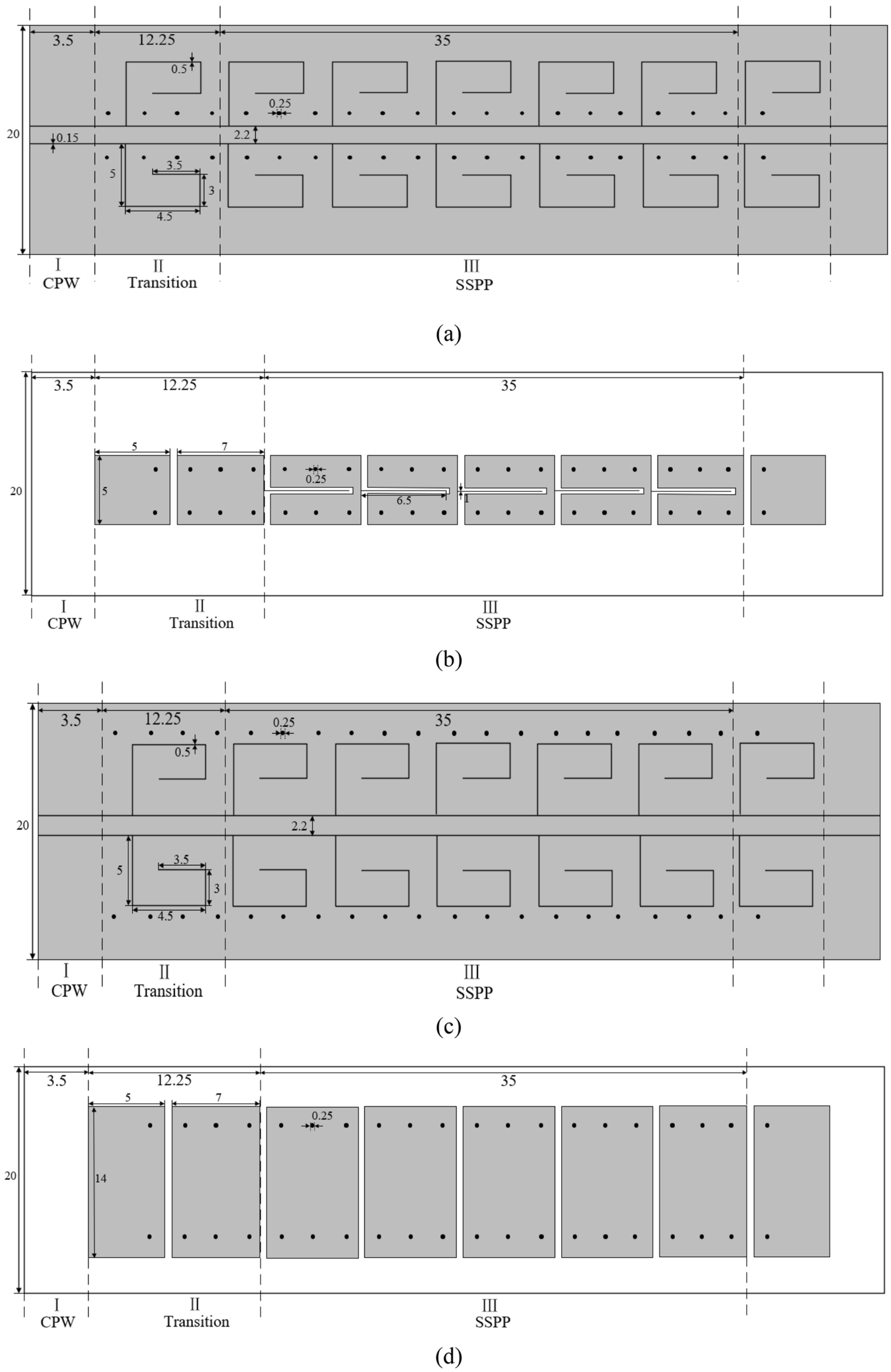


Fig. 5 The schematic configurations. **a** The top layout of the proposed SSPP. **b** The bottom layout of the proposed SSPP. **c** The top layout of the conventional SSPP. **d** The bottom layout of the conventional SSPP (dimensions in mm)

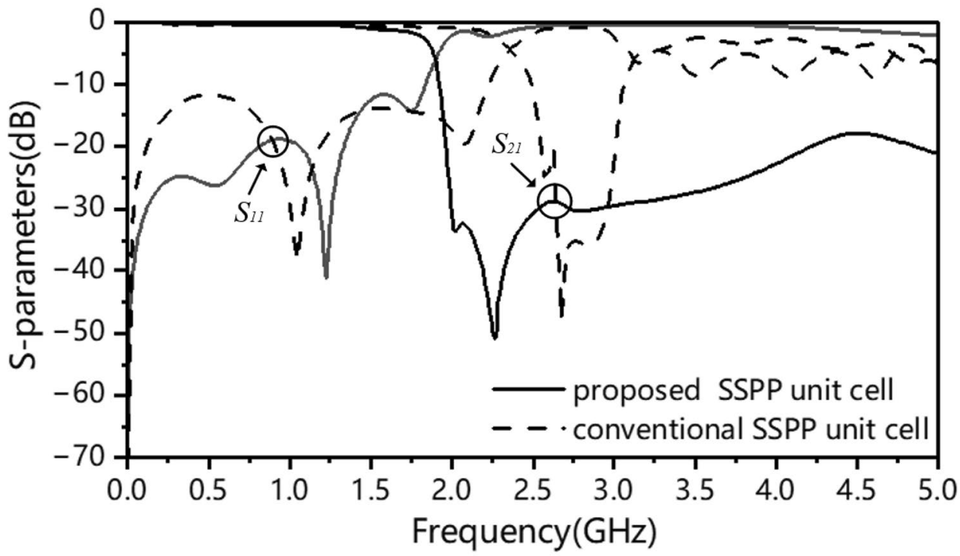


Fig. 6 Comparison of simulated S-parameters between the conventional and proposed SSPP unit cell

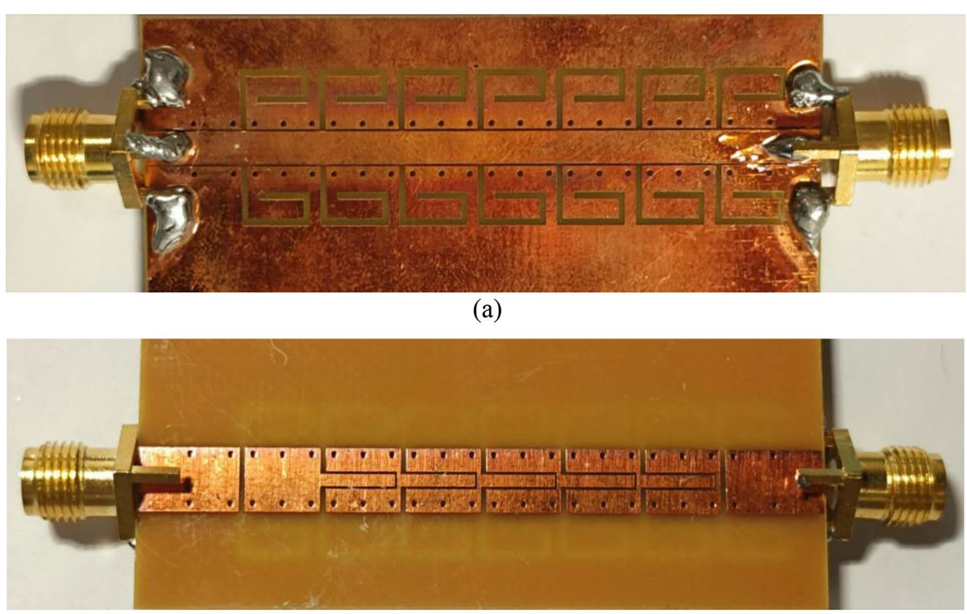
equivalent circuit computed and EM simulated dispersion curves with different l_l. The corresponding size parameters are set as follows: $w_l = 1$ mm, and l_l has three values of 1 mm, 3 mm, and 5.5 mm, respectively. From Fig. 4b, it can be observed that with the increase of l_l, the asymptotic frequency decreases, and the SSPP response becomes more pronounced.

Based on the above analysis, due to the extra inductance brought by the folded strip-type DGS structure, the proposed SSPP has a lower asymptotic frequency than the conventional SSPP, which is beneficial to the size reduction of the whole system. Besides, the size-reduction effect can be flexibly adjusted by changing the geometric parameters of the folded structure.

Fabrication and Measurement

The conventional GCPW SSPP and proposed PGCPW SSPP are shown in Fig. 5. It can be observed that these SSPP TLs consist of three different kinds of parts marked as I, II, and III, respectively. Part I is CPW region at two terminals. Part II is the transition region working as a mode converter and an impedance transformer to connect Part I and Part III. Part III is the SSPP transmission waveguide. The dimension parameters of the conventional and designed SSPP TLs are set as follows: $l_{s1} = l_1 = 5$ mm, $l_{s2} = l_2 = 4.5$ mm, $l_{s3} = l_3 = 3$ mm, $l_{s4} = l_4 = 3.5$ mm, $w_p = w_d = 0.15$ mm, $w_m = w_n = 2.2$ mm.

To validate the lower asymptotic frequency of the proposed SSPP TL, Fig. 6 compares the simulated S-parameters



(a)

(b)

Fig. 7 **a** Top view of the fabricated CPW SSPP TL. **b** Bottom view of the fabricated CPW SSPP TL

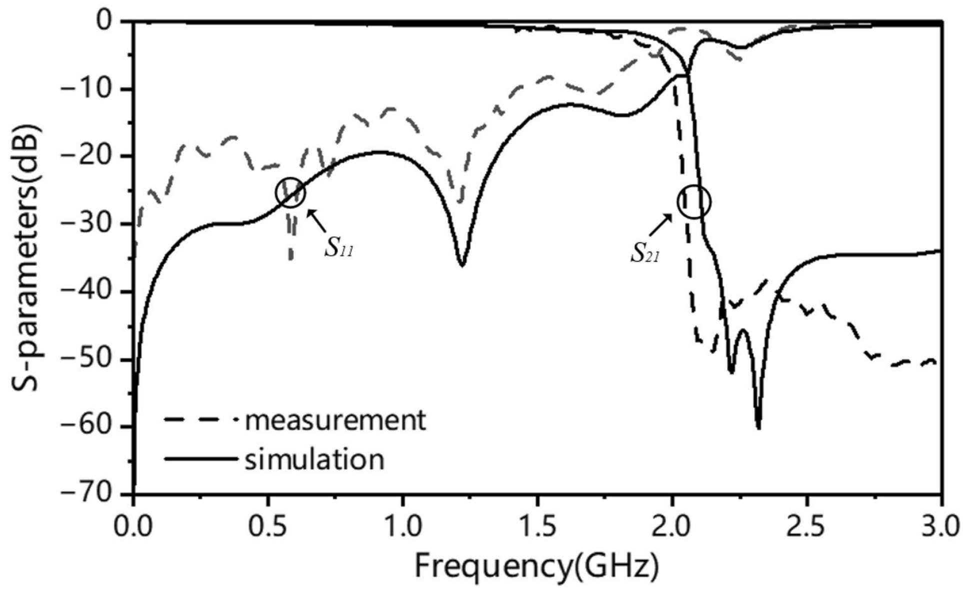


Fig. 8 Simulated and measured S-parameters

between the conventional and proposed SSPP TLs. It can be observed that the asymptotic frequencies of the conventional and proposed SSPP TL are 2.02 GHz and 1.73 GHz, which indicates that the proposed SSPP TL has more compact size than the conventional one with similar response.

We also fabricated the designed SSPP TL, and its top and bottom views are shown in Fig. 7a and b, respectively. Figure 8 depicts the measured and simulated S-parameters. It can be easily observed that the measured results are in accordance with the simulated ones, and the -3dB asymptotic frequency is only 1.845 GHz, implying its ultra-strong ability of field confinement. The difference between simulated results and measured results may be attributed to fabrication tolerances and measurement environment.

It should also be noticed that the size of the proposed SSPP TL unit cell is only 10 mm × 20 mm, which corresponds to 0.0064 λ_a^2(0.057 λ_a × 0.113 λ_a), where λ_a is the free space wavelength at the asymptotic frequency. For comparison, performances of the proposed SSPP TL and some previous SSPP TLs are listed in Table 3 in terms of asymptotic frequency f_a, unit size, transition structure size, and overall size. It can be observed that the proposed SSPP TL exhibits more compact unit size, transition size, and overall size.

Table 3 Performance of previous works and this work

Ref	f_a (Ghz)	*Unit size* (λ_a^2)	*Transition size* (λ_a^2)	*Overall size* (λ_a^2)
[7]	7.9	0.058	0.504	1.813
[8]	8.1	0.156	1.296	6.480
[9]	5.8	0.241	2.870	11.360
[10]	17.6	0.405	2.464	7.060
[11]	8.9	0.213	0.31	1.880
[12]	9.2	0.234	1.919	6.692
[13]	8	0.068	0.135	0.915
[14]	6	0.100	0.728	3.00
[15]	8.9	0.057	0.249	0.933
This work	1.7	0.006	0.008	0.043

Conclusion

A new SSPP TL based on partially grounded coplanar waveguide (PGCPW) is proposed in this paper. The analysis based on simulation results shows that the proposed SSPP TL has a lower asymptotic frequency, improved impedance matching, and a simple mode conversion structure Therefore, a compact PGCPW SSPP TL was designed, fabricated, and tested based on the proposed structure. The measurement results indicate that the proposed PGCPW SSPP TL has an ultra-compact unit cell size, transition size, and overall size.

Author Contributions All authors contributed to the study conception and design. The first draft of the manuscript was written by Yu-Xin Cui, and all authors commented on previous versions of the manuscript. Material preparation, data collection, and analysis were performed by Y.-X. C. Y.X. Z. prepared Fig. 4. Methodology, review, and editing were performed by L. L. All authors read and approved the final manuscript.

Funding No funding was obtained for this study.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

References

1. Barnes WL, Dereux A, Ebbesen TW (2003) Surface plasmon subwavelength optics. Nature 424(6950):824–30. https://doi.org/10.1038/nature01937
2. Garcia-Vidal FJ, Martin-Moreno L, Pendry JB (2005) Surfaces with holes in them: new plasmonic metamaterials. J Opt A Pure Appl Opt 7(2):S97. https://doi.org/10.1088/1464-4258/7/2/013
3. Pitarke JM, Silkin VM, Chulkov EV, Echenique PM (2006) Theory of surface plasmons and surface-plasmon polaritons. Rep Prog Phys 70(1):1–87. https://doi.org/10.1088/0034-4885/70/1/R01
4. Wei D, Li J, Yang J, Qi Y, Yang G (2018) Wide-scanning-angle leaky-wave array antenna based on microstrip SSPPs-TL. IEEE Antennas Wirel Propag Lett 17(8):1566–1570. https://doi.org/10.1109/LAWP.2018.2855178
5. Wang S, Chung KL, Kong F, Du L, Li K (2023) A simple circularly polarized beam-scanning antenna using modulated slotline-spoof surface plasmon polariton slow-wave transmission line. IEEE Antennas Wirel Propag Lett 22(5):1109–1113. https://doi.org/10.1109/LAWP.2022.3233677
6. Pendry JB, Martín-Moreno L, Garcia-Vidal FJ (2004) Mimicking surface plasmons with structured surfaces. Science 305(5685):847–848. https://doi.org/10.1126/science.1098999
7. Xu J, Li Z, Liu LL, Chen C, Xu BZ, Ning PP, Gu CQ (2016) Low-pass plasmonic filter and its miniaturization based on spoof surface plasmon polaritons. Opt Commun 372:155–159. https://doi.org/10.1016/j.optcom.2016.04.017
8. Shi Z, Shen Y, Hu S (2020) Spoof surface plasmon polariton transmission line with reduced line width and enhanced field confinement. Int J RF Microw Comput-Aid Eng 30(8):1–6. https://doi.org/10.1002/mmce.22276
9. Tang X-L, Zhang Q, Hu S, Kandwal A, Guo T, Chen Y (2017) Capacitor-loaded spoof surface plasmon for flexible dispersion control high-selectivity filtering. IEEE Microw Wirel Compon Lett 27(9):806–808. https://doi.org/10.1109/LMWC.2017.2734738
10. Xu H, Zhao W-S, Wang D-W, Liu J (2022) Compact folded SSPP transmission line and its applications in low-pass filters. IEEE Photonics Technol Lett 34(11):591–594. https://doi.org/10.1109/LPT.2022.3173657
11. Wang S, Chung KL, Du L, Kong F, Li K (2022) Design and analysis of a compact frequency beam-scanning antenna based on composite FHMSIW/SSPP waveguide. IEEE Antennas Wirel Propag Lett 21(3):546–550. https://doi.org/10.1109/LAWP.2021.3138151
12. Zhang DW, Zhang K, Wu Q, Ding XM, Sha XJ (2017) High-efficiency surface plasmonic polariton waveguides with enhanced low-frequency performance in microwave frequencies. Opt Express 25(3):2121–2129. https://doi.org/10.1364/OE.25.002121
13. Zhang DW, Liu X, Sun YX, Zhang K, Wu Q, Li YS, Jiang T (2022) Compact transition enabled broadband propagation of spoof surface plasmon polaritons based on the equivalent circuit model. J Phys D Appl Phys 55(16):165–165. https://doi.org/10.1088/1361-6463/ac4a35
14. He PH, Zhang HC, Gao XX, Niu LY, Tang WX et al (2019) A novel spoof surface plasmon polariton structure to reach ultra-strong field confinements. Opto-Electron Adv 2:190001. https://doi.org/10.29026/oea.2019.190001
15. Li JX, Shi JW, Xu KD, Guo YJ, Zhang AX, Chen Q (2020) Spoof surface plasmon polaritons developed from coplanar waveguides in microwave frequencies. IEEE Photonics Technol Lett 32(22):1431–1434. https://doi.org/10.1109/LPT.2020.3031065