Ultra-compact on-chip spoof surface plasmon polariton transmission lines with enhanced field confinements

Pei Hang He1,2, Dayue Yao1, Hao Chi Zhang1,2,∗, Jiangpeng Wang1, Di Bao1,2 and Tie Jun Cui1,2,∗

1 State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096, People’s Republic of China
2 Institute of Electromagnetic Space, Southeast University, Nanjing 210096, People’s Republic of China
∗ Authors to whom any correspondence should be addressed.

E-mail: hczhang0118@seu.edu.cn and tjcui@seu.edu.cn

Keywords: spoof surface plasmon polariton, chip, field confinement, miniaturization

Abstract

On-chip transmission lines (TLs) for spoof surface plasmon polariton (SSPPs) have been proved to suppress on-chip channel crosstalk in terahertz band due to their field confinement property. But the contradiction between strong field confinement and miniaturization limits the application of the on-chip SSPP TLs in millimeter and terahertz bands. Here, an ultra-compact on-chip SSPP TL with strong field confinement is proposed using 0.18 µm CMOS technology. The proposed SSPP TL reduces the cutoff frequency down to 435 GHz in a very limited TL width. Broadband feeding without using gradient transition structures is presented to guarantee the compact size. Compared to microstrip and the typical SSPP TLs, outstanding field confinement of the novel on-chip SSPP TL is demonstrated by the electrical-field-intensity distributions. Measured result matches to simulated one well. It is shown that the proposed on-chip SSPP TL possesses the lowest cutoff frequency and the smallest width relative to the cutoff wavelength, compared to the microstrip and the typical SSPP TLs. Thus the ultra-compact on-chip SSPP TL with strong field confinement may be widely used in the future miniaturized monolithic microwave integrated circuits.

1. Introduction

Surface plasmon polaritons (SPPs) [1, 2] are highly localized surface waves with strong field confinements. According to the Maxwell’s equations, SPPs are excited on the interfaces of two media with opposite permittivity, where the negative permittivity is available in the optical band due to the plasmonic behavior of metals. However, metals behavior as conductor rather than plasmonic materials in the lower terahertz, millimeter wave and microwave bands. To apply the outstanding physical properties of SPPs into terahertz and microwave engineering, the new method to realize equivalent negative permittivity has to be found. Thus, the concept of spoof SPPs (SSPPs) supported by periodic subwavelength structures were developed [3–8]. Among the SSPP structures, ultrathin SSPP structures, also called as SSPP waveguides or SSPP transmission lines (TLs) [9–14], emerge both great compatibility with modern planar circuit technology and novel advantages compared to the traditional microwave media, including low crosstalk [15–17], miniaturized packaging [18, 19] and customizable dispersion [20]. Based on these merits, many novel devices have been reported, including filters [21–23], antennas [24–27], amplifiers [28, 29], harmonic generators [30, 31] and multifunctional device [32–34]. In 2020, the first SSPP-based wireless communication system was demonstrated [35], showing the value of the SSPP technology at the system level.

In recent years, on-chip SSPP TLs have become an attractive research topic to explore the new path to the highly integrated circuits and systems. In 2015, an on-chip sub-terahertz SSPP TL in CMOS was reported [36], where the configuration of strip with periodic straight stubs was used. Afterwards, several works on the SSPP-based chips using the typical SSPP TL configurations were proposed to realize low-loss transmission [37], spatial radiation [38], high-speed communication [39–41] and dynamic manipulation [42]. As we can...
see, most of the reported on-chip SSPP TLs possess the cutoff frequency in the terahertz band, which indicate that the field confinement of the SSPPs in millimeter band is relatively weak. However, if stronger field confinement in the millimeter or sub-terahertz band is expected, much larger spaces are needed according to the working principle of the typical SSPP TLs [43]. In [38], for example, a width larger than 40 µm is needed for the SSPP TL to realize cutoff frequency lower than 700 GHz, though the miniaturized single-side structure has been used. Considering the limited areas of chips, it is essential to resolve the contradiction between strong field confinement and miniaturization of the on-chip SSPP TLs.

In this work, a novel ultra-compact on-chip SSPP TL with enhanced field confinement is proposed to realize strong field confinement and miniaturization of on-chip SSPP TLs simultaneously. Firstly, the geometrical parameters of the SSPP TL are introduced. Next, the dispersion property of the SSPP TL is investigated. Then, the method to feed the proposed SSPP TL is presented without using cumbersome gradient transition. Moreover, electrical-field-intensity distributions of the proposed SSPP TL are shown to demonstrate the enhanced field confinements of the ultra-compact on-chip SSPP TL compared to the microstrip and the typical SSPP TLs. Finally, a sample of the ultra-compact SSPP TL is fabricated for measurement.

2. Design and modeling

For convenience of comparison, all TLs in this letter are designed using the 0.18 µm CMOS technology, as shown in figure 1(a). The M2 layers are selected as the ground layers. The M6 layer is selected as the signal line layer, where the vertical view. The minimum metallic width and space of M6 are 2.6 µm. The permittivities of the passivation layer #1, passivation layer #2, inter-metal-dielectric #1 and inter-metal-dielectric #2 are 4.2, 4.2, 3.8 and 3.7, respectively. The typical on-chip SSPP TL with periodic straight stubs is shown in figure 1(b), in which the TL width \( w_1 \) can be modified to control the dispersion curve, and the other geometrical parameters are fixed as \( s_1 = 2.6 \) µm, \( a_1 = 2.6 \) µm and \( p_1 = 16.25 \) µm. In this work, dispersion curves of the SSPP TL unit are carried out using the Eigen-mode simulation of commercial software, CST Microwave Studio. It can be observed from figures 2(a) and (b) that changing \( a_1 \) and \( p_1 \) will affect the cutoff frequency of the typical on-chip SSPP TL negligibly. In other words, \( a_1 \) and \( p_1 \) are not the key parameters for the typical on-chip SSPP TL. The cutoff frequency will increase if \( s_1 \) is greater than 2.6 µm. Hence, for the typical on-chip SSPP TL, \( s_1 \) with the value of 2.6 µm fits the best working condition for the typical on-chip SSPP TL. As shown in figure 2(c), cutoff frequency of the dispersion curves of SSPPs is reduced with the increase of TL width, which leads to stronger field confinement at the cost of larger chip space [43].

To resolve the contradiction between field confinement and miniaturization of the on-chip SSPP TLs, we propose a new on-chip SSPP TL with periodic meander stubs, as shown in figure 1(c), in which the geometrical parameters are fixed as \( w_2 = 23.4 \) µm, \( s_2 = 2.6 \) µm, \( a_2 = 2.6 \) µm and \( p_2 = 65 \) µm. Dispersion curves of the new on-chip SSPP TL is shown in figure 2(b). Different from the typical on-chip SSPP TL in figure 1(b), dispersion curve of the new on-chip SSPP TL with a fixed TL width is controlled by order of the meanders \( N_1 \), as shown in figures 2(c)–(g). It can be observed from figures 2(a) and (b) that this new SSPP TL can achieve cutoff frequency of 435 GHz within the TL width of 23.4 µm, while a TL width of 164 µm is needed for the typical one.

Considering the limited space of chips, the gradient transition structure [44, 45] is not favored for realizing miniaturization of SSPP-based chips. Thus, microstrips are utilized to feed the proposed SSPP TL [46], as shown in figure 3. Width of the 40 Ω microstrip \( w_{\text{m}} \) is 10 µm, and the simulated reflection and transmission of the whole structure is shown in figure 4. It can be observed that a good conversion in the band of 0–360 GHz between microstrip ports and the proposed SSPP TL is realized.

For visualizing the merit of strong field confinement of the proposed ultra-compact SSPP TL, electrical-field-intensity distributions of the microstrip, the typical SSPP TL and the new ultra-compact SSPP TL at 350 GHz are compared, as shown in figures 5(a)–(c). The three TLs are all with the TL width of 23.4 µm. It can be observed in figures 5(a)–(c) that fields of both the typical SSPP TL and the ultra-compact SSPP TL are confined more tightly than that of the microstrip. According to the dispersion analysis, even though the typical SSPP TL and the ultra-compact SSPP TL possess identical TL width, field confinement of the latter one is much stronger than the former one, which is clearly verified in figures 5(b) and (c) as well. Hence, the visualized enhanced field confinements of the ultra-compact SSPP TL matches well with the deduction obtained from the dispersion analysis in figure 2. Moreover, electric fields along the radial direction of three TLs are shown in figure 5(d). As the monitoring point moves away from the center point, we observe that the electric field of the ultra-compact SSPP TL attenuates faster than that of the typical SSPP TL and microstrip, which demonstrates the enhanced field confinements of the ultra-compact SSPP TL quantitatively. The field confinement can be described by the distance corresponding to a specified threshold.
of electric field in radial direction as well. For instance, if we set $65 \text{ dB(V m}^{-1})$ as the threshold of the electric field, the distances of the microstrip, the typical SSPP TL and the ultra-thin SSPP TL are $119 \mu\text{m}$, $96 \mu\text{m}$ and $86 \mu\text{m}$, respectively.

The comparison of the proposed on-chip SSPP TL and previous works is listed in table 1. Although the physical TL width of this work is not the smallest compared to some previous works, the lowest cutoff frequency is achieved by this work. And we can find that the proposed on-chip SSPP TL possesses the smallest width relative to cutoff wavelength, which resolves the contradiction between field confinement and miniaturization of on-chip SSPP TLs significantly.

### 3. Experiment

Layout of the new SSPP TL is shown in figure 6(a). Geometrical parameters of the grounded coplanar waveguide (GCPW) pads for probe connection are set as $l_1 = 80 \mu\text{m}$, $l_2 = 75 \mu\text{m}$, $l_3 = 50 \mu\text{m}$, $l_4 = 25 \mu\text{m}$, $l_5 = 183 \mu\text{m}$, $l_6 = 38 \mu\text{m}$ and $l_7 = 8 \mu\text{m}$. It should be noted that the geometrical parameters of GCPW pads are depended on the specific process line, and the low degree of freedom of the GCPW pads may lead to impedance mismatch when exciting chips. Thus, impedance matching has to be with width of $10 \mu\text{m}$ and length $l_8 = 10 \mu\text{m}$ is used to connect the proposed SSPP TL. Since mismatch caused by the pad cannot be ignored in millimeter band, a short-circuit stub with width of $2.6 \mu\text{m}$ and length $l_9 = 50 \mu\text{m}$ is used to realize impedance match in the band near 200 GHz. A sample chip is fabricated for experimental demonstration of effective feeding of the proposed SSPP TL, as shown in figure 6(b). Considering the fact that the probe contacts nearly center of the pads, the equivalent circuit model of the connection is shown in figure 6(c), where a short-circuit stub described by electric length $\theta_s$ and characteristic impedance $Z_s$ is added for impedance matching. By modifying the length and characteristic impedance of the short-circuit stub, the relatively narrow-band matching of the probe-GCPW-SSPP connection can be achieved approximatively.
Figure 2. Dispersion curves of the SSPP TLs. (a) Dispersion curves of the typical on-chip SSPP TL with different $a_1$ and $s_1$, where the $w_1$ and $p_1$ are fixed at 23.4 $\mu$m and 16.25 $\mu$m, respectively. (b) Dispersion curves of the typical on-chip SSPP TL with different $p_1$, where the $a_1$, $s_1$ and $w_1$ are fixed at 2.6 $\mu$m, 2.6 $\mu$m and 23.4 $\mu$m, respectively. Here, since the change of $p_1$ will cause inconformity of $x$ axis, the $k_{p_0}$ is used as $x$ axis of the figure, where $p_0$ is fixed at 16.25 $\mu$m. (c) Dispersion curves of the typical on-chip SSPP TL with different $w_1$, where the $a_1$, $s_1$ and $p_1$ are fixed at 2.6 $\mu$m, 2.6 $\mu$m and 16.25 $\mu$m, respectively. (d) Dispersion curves of the ultra-compact on-chip SSPP TL with different order of the meanders $N$. (e)-(g) Unit of the ultra-compact on-chip SSPP TL with different $N$.

Figure 3. Exciting the ultra-compact SSPP TL using microstrips.

Measured reflection and transmission in the band from 0 to 325 GHz are shown in figure 7, which matches the simulated ones well. It can be observed that a flat passband ($\pm 0.5$ dB) is realized in the band of 159–220 GHz (fractional bandwidth of 32.2%).
Figure 4. Reflection and transmission of the whole ultra-compact SSPP TL.

Figure 5. Field confinement of different TLs. (a)–(c) Electrical-field-intensity distributions of (a) the microstrip, (b) the typical SSPP TL and (c) the ultra-compact SSPP TL at 350 GHz. (d) Electric fields along the radial direction of the three TLs.
Table 1. Comparison with previous works.

| Reference | Technology   | Structure   | TL width (µm) | Cutoff frequency (GHz) | TLwidth relative to cutoff wavelength (%) |
|-----------|--------------|-------------|---------------|------------------------|-------------------------------------------|
| [21]      | 65 nm CMOS   | Single side | 6             | 4600                   | 9.2%                                      |
| [22]      | 130 nm BiCMOS| Double side | 20            | 4600                   | 30.7%                                     |
| [23]      | 65 nm CMOS   | Double side | 27            | 2400                   | 21.6%                                     |
| [26]      | 65 nm CMOS   | Single side | 35            | 750                    | 7.5%                                      |
| This work | 0.18 µm CMOS | Double side | 23.4          | 435                    | 3.4%                                      |

Figure 6. Experiment of the ultra-compact SSPP TL. (a) Layout of the ultra-compact SSPP TL. (b) Die micrograph of the ultra-compact SSPP TL. (c) Measured and simulated S-parameters.
4. Conclusion

In summary, an ultra-compact on-chip SSPP TL with strong field confinement is proposed. Compact feeding and good field confinement of the SSPP TL are demonstrated. Compared to the previous works, the novel ultra-compact on-chip SSPP TL possesses the lowest cutoff frequency and the smallest TL width relative to the cutoff wavelength. In fact, since the new method to reduce the cutoff frequency of SSPPs by using periodic meander stubs without increasing the TL’s width is validated, the designing method of the proposed on-chip SSPP TL may be widely used in the future miniaturized monolithic microwave integrated circuits, where the limitation of TL width is stricter than that of the TL unit period.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

Pei Hang He and Dayue Yao contribute equally to this work. This work was supported in part from the National Natural Science Foundation of China under Grant Nos. 62101122 and 61871127, in part from the Natural Science Foundation of Jiangsu Province under Grant No. BK20210212, in part from the Zhishan Scholar Program of Southeast University, in part from the Fundamental Research Funds for the Central Universities under Grant No. 2242022R40007, and in part from the 111 Project under Grant No. 111-2-05.

ORCID iDs

Pei Hang He https://orcid.org/0000-0002-2730-8895
Tie Jun Cui https://orcid.org/0000-0002-5862-1497

References

[1] Barnes W L, Dereux A and Ebbesen T W 2003 Nature 424 824–30
[2] Wen X M 2021 Opto-Electron. Adv. 4 200024
[3] Pendry J B, Martin-Moreno L and Garcia-Vidal F J 2004 Science 305 847–8
[4] Yu N, Wang Q J, Kats M A, Fan J A, Khanna S P, Li L, Davies A G, Linfield E H and Capasso F 2010 Nat. Mater. 9 730–5
[5] Woolf D, Kats M A and Capasso F 2014 Opt. Lett. 39 517–20
[6] Erementchouk M, Joy S R and Mazumder P 2016 Proc. R. Soc. A 472 20160616
...