EPJ Appl. Metamat. **9**, 7 (2022)
© Y. Lu et al., Published by EDP Sciences, 2022
https://doi.org/10.1051/epjam/2022010

EPJ Applied Metamaterials

Available online at:
epjam.edp-open.org

Metamaterial Research Updates from China

Research Article **Open Access**

Multi-layer transmission line of spoof surface plasmon polaritons

Yuxi Lu[1,2], Wenxuan Tang[1,2,*], and Tie Jun Cui[1,2]

[1] State Key Laboratory of Millimeter Waves, Southeast University, Nanjing 210096, PR China
[2] Institute of Electromagnetic Space, Southeast University, Nanjing 210096, PR China

Received: 23 January 2022 / Accepted: 21 March 2022

Abstract. In modern microwave technology, multi-layer structure is widely adopted in compact circuit design. In a multi-layer microwave system, the transmission line (TL) plays an important role. The multi-layer TLs need to have high cross-layer transmission efficiency, which is a big challenge in highly integrated circuits. Spoof surface plasmon polaritons (SSPP) possess good performance on field confinement and low transmission loss at microwave and terahertz frequencies, and can achieve the compact design in planar microwave circuits. In this article, a new type of multi-layer SSPP TL is proposed and tested. Taking advantage of the properties of SSPPs, the proposed TLs achieve high transmission efficiency for both in-layer and cross-layer situations. The proposed SSPP TLs have great prospect in the future multi-layer circuit design.

Keywords: Spoof surface plasmon polaritons (SSPPs) / transmission line (TL) / multi-layer circuit / cross-layer transmission

1 Introduction

Surface plasmon polaritons (SPP) is a special kind of surface electromagnetic (EM) wave existing on the interface of two media with opposite permittivities (e.g., metal and the air) in optical regime [1]. When the EM field of the incident waves interacts with the plasma of electrons near the surface of the metal, collective oscillations are excited and propagate along the interface in the SPP mode. The EM field is strongly localized to the interface, and therefore the SPPs hold the merits of enhanced field, sub-wavelength resolution, suppressed mutual interference, and so on. The SPP mode has been exploited in biosensing, microscopy, and near-field optics in plasmon-based circuits for its advantages [2,3]. However, the SPP mode only exists above the infrared band. At lower frequencies, metals behave close to perfectly electric conductors (PECs) instead of plasma, so the SPP mode cannot be stimulated. In order to make use of the dispersion and propagation properties of SPPs in lower band, spoof surface plasmon polaritons (SSPP) with periodically sub-wavelength perforated structure was proposed [4–6]. It has been experimentally demonstrated to inherit the excellent features of SPP in terahertz and microwave regimes.

Most recently, circuits composed of planar SSPP waveguides have been intensively investigated due to the increasing requirements on compact circuits and advanced systems. Planar SSPP waveguides, in particular, the SSPP transmission lines (TLs), are highly expected to offer new solutions to highly-integrated and reconfigurable circuits in view of their designable dispersion characteristics, extraordinary field confinement, sub-wavelength resolution, low crosstalk, and low interference with incident EM waves. A number of SSPP TLs, together with a series of SSPP based devices and antennas, have been delivered and verified, providing the basis for building advanced SSPP circuits and systems [7–10]. Different from traditional microwave TLs such as the microstrip (MS) lines, the dispersion characteristics of the SSPP TLs can be designed by tuning the geometric parameters of their sub-wavelength units, which provides convenience to design SSPP TLs with different properties and reconfigurability [11,12].

In the modern microwave circuit, more and more complex functions, signal paths and control devices ask for more compact and miniaturized design to efficient utilize the limited circuit area. Multi-layer design has been proved to be convenient and efficient for miniaturized circuit. In view of this, enormous numbers of researches and applications based on multi-layer circuits with microstrip lines have been conducted [13,14]. However, studies based on multi-layer SSPP TLs, which may have great prospects on compact circuit design due to the merits of SSPP, could hardly be found [15].

In this article, a kind of multi-layer SSPP TLs based on periodical groove structure is proposed. Simulation and experiment for the TL have been conducted to illustrate the transmission property. Impedance matching between different layers is proved to be a crucial factor to acquire high cross-layer transmission efficiency. The proposed SSPP TLs has shown great potential for future utilization in multi-layer circuit.

---

[*] e-mail: `wenxuant@seu.edu.cn`

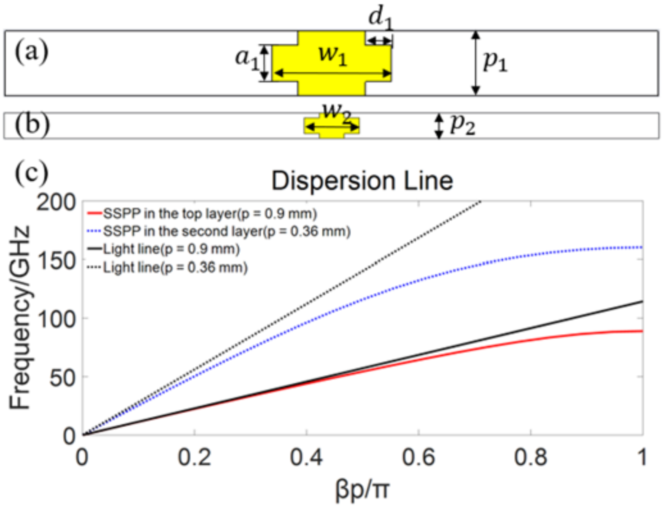

Fig. 1. (a) Sub-wavelength unit in the top copper layer. (b) Sub-wavelength unit in the second copper layer. (c) Dispersion curves of the SSPP TLs in different layers.

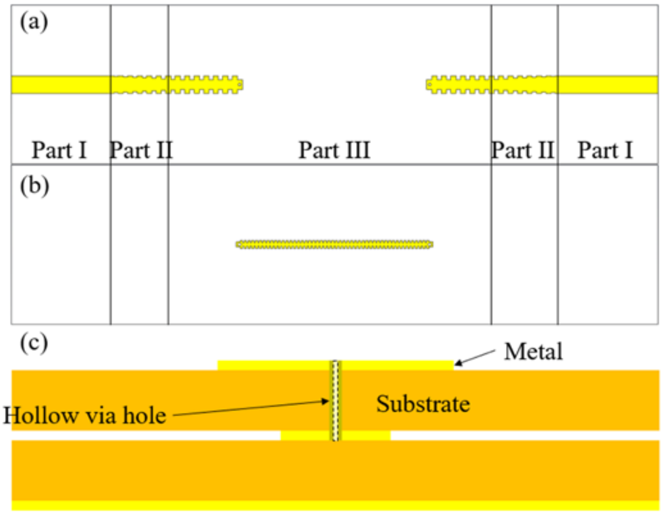

Fig. 2. The proposed multi-layer SSPP TL. (a) Top view of the top copper layer. (b) Top view of the second copper layer. (c) Sketch of the layer structure.

2 Methodology

In the multi-layer SSPP TL, three layers of 0.018 mm-thick copper conductor are separated by two layers of Rogers RT5880 substrate. The top two layers of copper are groove structures with sub-wavelength units, on which the SSPP waves are supported to propagate. The bottom layer is the ground. Dispersion and transmission properties of the SSPP TL are controlled by the geometry parameters of the units, and in view of this, the units in different copper layers and their dispersion properties are analyzed firstly. Eigen-mode Solver in the commercial software CST Microwave Studio is used to calculate the dispersion curves of the SSPP TL in different layers, in particular, the wider TL in the top layer of copper (see Fig. 1a) and the narrower one in the second layer of copper between two substrates (see Fig. 1b).

Dispersion curves of the units in different layers are plotted in Figure 1c, in which β represents the propagation constant and p the period in each layer. It can be noted that the propagation constants of the SSPPs are larger than that of light, and the dispersion curves deviate more with frequency getting higher, indicating that SSPPs hold the features of strong field localization. For the sub-wavelength unit in Figure 1a, the period, maximum line width, groove depth and tooth width are $p_1 = 0.90$ mm, $w_1 = 1.64$ mm, $d_1 = 0.36$ mm, and $a_1 = 0.50$ mm, respectively, while for the unit in Figure 1b, these values are $p_2 = 0.36$ mm, $w_2 = 0.76$ mm, $d_2 = 0.21$ mm, and $a_2 = 0.22$ mm. The different parameters in different layers are optimized and adopted to realize the impedance matching between different layers. It should be pointed out that although the dispersion curves of the SSPP TLs in different layers are different, impedance matching can be achieved with cross-layer transition as long as the impedances are matched at the interface of the two different SSPP units (which are at the cross-layer transition) [16]. Moreover, in this study we find that the line widths (w_1 and w_2) are the most important factor to be optimized for high-efficiency transmission, as demonstrated in simulation and experiment.

The designed SSPP TL is shown in Figure 2. The dielectric constant of RT5880 is 2.2, the loss tangent is 0.0037, and the thickness is 0.254 mm. The first and the second layers of SSPP TLs are connected by hollow-cylinder shaped via holes. The radius and inner wall thickness of the via holes are 0.15 mm and 0.025 mm respectively, while the distance between the edges of the via and the surrounded pad is at least 0.1 mm. The line widths of the top layer (w_1) and the second layer (w_2) are respectively 1.64 mm and 0.76 mm, which are exactly the line widths for 50 Ω microstrip at each layer. Because the SSPP TL is fed with the microstrip lines (shown as Part I in Fig. 2) and matched at the cross-layer transition, impedance matching is also guaranteed for the SSPP TLs with the values of w_1 and w_2, which will be further verified by the simulation and experimental results below. As a whole, the multi-layer SSPP TL is composed of three parts as denoted in Figure 2. Part I is the 50 Ω microstrip line that is connected to the external feeding port. Part II is gradient grooves for impedance and momentum transition between microstrip line and SSPP TL. Part III is the uniform SSPP TL in two copper layers. The scattering parameters (S-parameters) with different w_1 and w_2 of the SSPP TLs simulated by CST Microwave Studio are shown in Fig. 3. It can be observed that the transmission coefficient (S21) is higher than -1.5 dB and the reflection coefficient (S11) is lower than -17 dB from 0–40 GHz when the impedance of the two layers are matched to 50 Ω (case A). In contrast, when impedance matching is not satisfied, e.g., in case B, C, and D in Figure 3, S-parameters will obviously deteriorate. Therefore, it can be concluded that the impedance matching is the most important factor that should be firstly considered in cross-layer design for SSPP TLs.

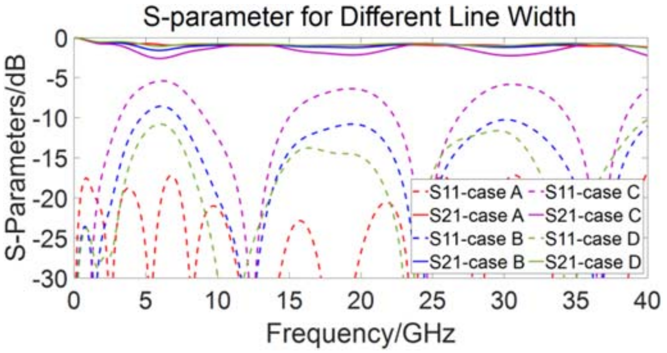

Fig. 3. S-parameters for SSPP TLs with different line widths w_1 and w_2 for different layers. Case A ($w_1 = 1.64$ mm, $w_2 = 0.76$ mm), Case B ($w_1 = 1.64$ mm, $w_2 = 1.20$ mm), Case C ($w_1 = 1.64$ mm, $w_2 = 1.64$ mm), Case D ($w_1 = 1.20$ mm, $w_2 = 0.76$ mm). (The depths of the SSPP units proportionally change with the line widths).

3 Simulation and experiment

To verify the performance of the proposed multi-layer SSPP TL, numerical simulations for six different TLs with different numbers of via holes and units as listed in Table 1 have been conducted. The simulated S-parameters are shown in Figure 4a and 4b. For all TLs, S21 are all higher than −1.5 dB, and S11 are all lower than −13 dB from 0 to 40 GHz, exhibiting good transmission and low reflection. Comparing different cases, the S21 for the TLs with 4 via holes (Cases 4, 5, 6) are slightly lower than the corresponding ones with 2 via holes (Cases 1, 2, 3). Around 15 GHz, each via hole will bring about 0.02 dB transmission loss. Comparing the differences of S21 between Case 1 and Case 2, and between Case 4 and Case 5, the insertion loss in the second layer SSPP TL is about 0.12 dB/cm around 15 GHz. Similarly, comparing the differences of S21 between Case 1 and Case 3, and between Case 4 and Case 6, the insertion loss of the top layer SSPP TL is about 0.14 dB/cm around 15 GHz. The transmission loss per unit length of the top layer is slightly higher than that of the second layer, which may be due to the energy loss to the free space. However, as the frequency goes higher, the losses of the via holes and the SSPP TLs will increase. In the frequency range of 20–40 GHz, the maximum loss of each via hole is about 0.21 dB, and the transmission losses in the top layer and the second one is 0.40 dB/cm and 0.45 dB/cm respectively. The average transmission loss in the second layer will be slightly higher than that in the top layer at high frequencies, e.g. 30–40 GHz, which may be mainly due to the increases of substrate loss at high frequencies. From the electric field distribution in Figure 4c, which shows the electric field for Case 2 at 20 GHz, it is also confirmed that the SSPP wave propagates with high efficiency for both in-layer and cross-layer situations.

Samples of the six different SSPP TLs are all manufactured and tested, and the testing platform is shown in Figure 5. The top substrate layer and the second conductor layer are bonded by 0.1 mm-thick polypropylene glue, with its dielectric constant being 2.8. Two weld-free joint connectors are used to feed the SSPP TLs, and A 0–40 GHz Agilent Vector Network Analyzer (VNA) is the test apparatus. Figure 6 shows the measurement results of the six SSPP TLs. It can be observed that, the measured S-parameters agree well with the simulation in the low frequency band, and get worse over 20 GHz. The transmission coefficients (S21) for all the cases are higher than −3 dB below 20 GHz, except for Case 4 over 18 GHz. And then, the insertion losses are less than 6 dB up to 30 GHz and 10 dB up to 40 GHz for most cases. As for the reflection coefficients, S11 is less than −10 dB below 20 GHz for all cases and less than −5 dB up to 40 GHz for most cases. The deterioration in high frequency band may be attributed to the machining error and sample assembly, and also the loss of substrate and glue at high frequencies. Nevertheless, the multi-layer SSPP TL possesses great transmission and low reflection below 20 GHz, and therefore becomes a good candidate of new-type multi-layer transmission line.

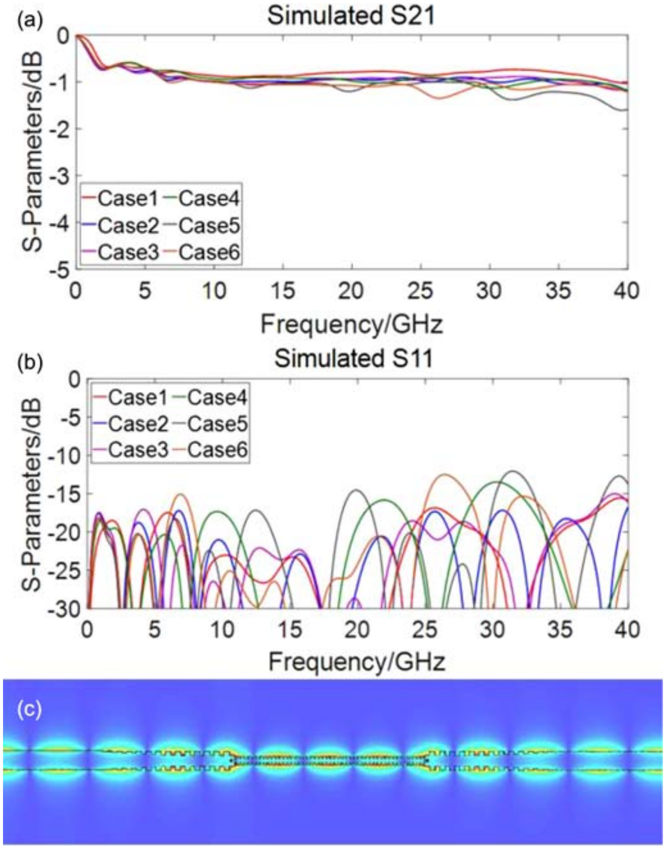

Fig. 4. (a) The simulated S21 for the 6 cases of the SSPP TLs. (b) The simulated S11 for the 6 cases of the SSPP TLs. (c) The simulated electric field distribution of the multi-layer SSPP TL (Case 2 at 20 GHz).

4 Conclusion

In this article, a multi-layer SSPP TL is proposed to achieve high-efficiency cross-layer transmission. The

Table. 1. Cases of Multi-Layer SSPP TLs.

	Number of via holes	Number of SSPP units in the top layer	Number of SSPP units in the second layer	Total length (mm)
Case 1	2	12	20	50.40
Case 2	2	12	50	61.20
Case 3	2	24	20	61.20
Case 4	4	12	20	50.40
Case 5	4	12	50	61.20
Case 6	4	24	20	61.20

simulation and experiment for six different cases have been conducted, demonstrating that the insertion loss of the new-type multi-layer TL is less than 3 dB and the reflection is lower than −10 dB below 20 GHz. The properties in higher frequency band in the experiment are not as good, which is mainly due to the high-frequency substrate loss, machining error and assembly problem. The results show great in-layer and cross-layer transmission properties for multi-layer SSPP TLs, and suggest that the proposed SSPP TL have great prospects in future multi-layer circuit systems.

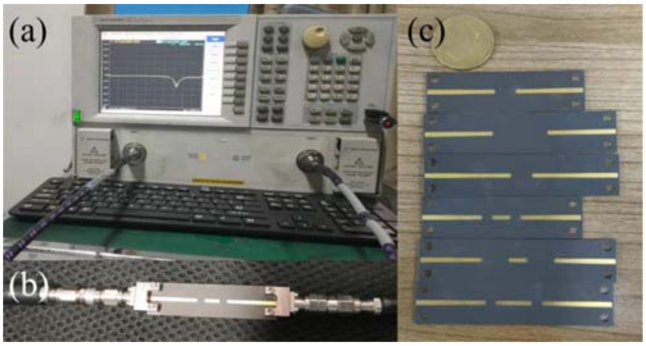

Fig. 5. (a, b) The test system of the experiment. (c) The measured samples of the 6 cases. The samples of case 1 to case 6 are arranged in order from the top to the bottom of the photo.

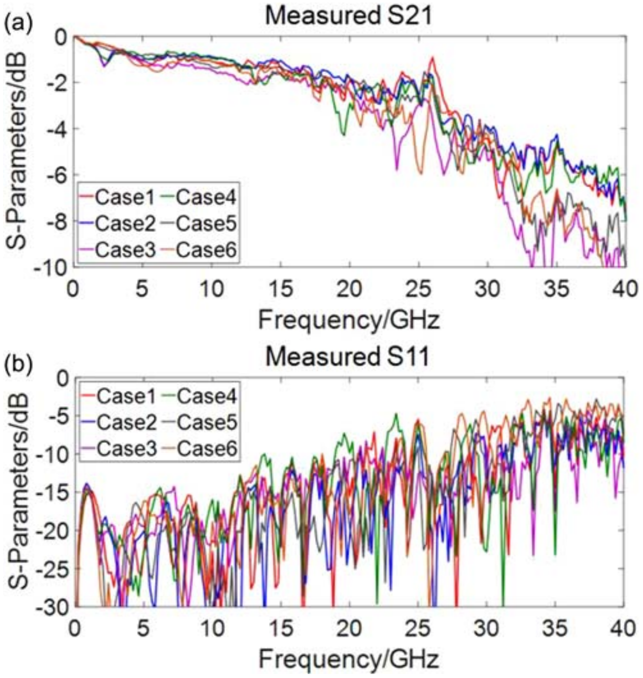

Fig. 6. (a) The measured S21 for the 6 cases of the SSPP TLs. (b) The measured S11 for the 6 cases of the SSPP TLs.

This work is supported by the National Key Research and Development Program of China (2021YFB3200502), the National Natural Science Foundation of China (61971134, 61631007), the Fundamental Research Funds for the Central Universities (2242021R41078), and the 111 Project (111-2-05).

References

1. H. Raether, Surface Plasmons on Smooth and Rough Surfaces and on Gratings (Springer, Berlin, Heidelberg, Berlin, 1988)
2. N. Fan, H. Lee, C. Sun, X. Zhang, Science **308**, 534 (2005)
3. M. Ozaki, J. Kato, S. Kawata, Science **332**, 218 (2011)
4. J.B. Pendry, L. Martin-Moreno, F.J. Garcia-Vidal, Science **305**, 847 (2004)
5. S.A. Maier, S.R. Andrews, L. Martin-Moreno, F.J. Garcia-Vidal, Phys. Rev. Lett. **97**, 176805 (2006)
6. A.P. Hibbins, B.R. Evans, J.R. Sambles, Science **308**, 670 (2005)
7. X. Shen, T.J. Cui, D. Martin-Cano, F.J. Garcia-Vidal, Proc. Natl. Acad. Sci. USA **110**, 40 (2013)
8. W.J. Zhang, G.Q. Zhu, L.G. Sun, F.J. Lin, Appl. Phys. Lett. **106**, 021104 (2015)
9. G.S. Kong, H.F. Ma, B.G. Cai, T.J. Cui, Sci. Rep. **6**, 29600 (2016)
10. H.C. Zhang, S. Liu, X. Shen, L.H. Chen, L. Li, T.J. Cui, Laser Photonics Rev. **9**, 83 (2015)
11. H.C. Zhang, T.J. Cui, J. Xu, W.X. Tang, J.F. Liu, Adv. Mater. Technolog. **1**, 1600202 (2017)
12. M. Wang, H.F. Ma, W.X. Tang, S. Sun, T.J. Cui, Phys. Rev. App. **12**, 014036 (2019)

13. F. Cai, Y. H. Chang, K. Wang, C. Zhang, B. Wang, J. Papapolymerou, IEEE Trans. Microwave Theory Tech. **64**, 3208 (2016)
14. B.K. Tehrani, B.S. Cook, M.M. Tentzeris, IEEE Antennas Wireless Propag. Lett. **15**, 143 (2015)
15. B.C. Pan, J. Zhao, Z. Liao, H.C. Zhang, T.J. Cui, Sci. Rep. **6**, 22702 (2016)
16. P.H. He, Y. Fan, H.C. Zhang, L.P. Zhang, M. Tang, M. Wang, L.Y. Niu, W. Tang, T.J. Cui, J. Phys. D: Appl. Phys. **54**, 385102 (2021)

Cite this article as: Yuxi Lu, Wenxuan Tang, Tie Jun Cui, Multi-layer transmission line of spoof surface plasmon polaritons, EPJ Appl. Metamat. **9**, 7 (2022)