Frequency Splitting Based on Spoof Surface Plasmon Polaritons Coplanar Waveguide

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Abstract ─ In this paper, a novel frequency splitter is proposed based on the spoof surface plasmon polaritons (SSPPs) coplanar waveguide (CPW). The proposed frequency splitter uses the semi-circular holes etched on the both sides of the middle line of the CPW to realize mode conversion and frequency splitting. The operating principles of the proposed frequency splitter have been analyzed by the dispersion curves, electric field distributions, and equivalent circuit. Moreover, the splitting frequency of the splitter can be easily controlled by changing the corresponding parameters. Furthermore, full-wave simulation along with the measured results are given to describe the performance of the proposed frequency splitter. The highly consistent between simulated and measured results validates the design conception, which means that the proposed design is of importance to develop surface-wave integrated circuits.

Index Terms ─ Coplanar waveguide, frequency splitter, spoof surface plasmon polaritons.

I. INTRODUCTION

Spoof surface plasmon polaritons (SSPPs) have been widely used to design various microwave SSPP-based antennas [1-4], low-pass or band-pass filters [5-11], and power dividers [12-22]. According to its specific performance of confining fields, various SSPP structures were proposed (such as flaring grounds, gradient corrugation slits, lumped elements, and hole array) to design miniaturized devices.

Power divider is a key component in microwave communication systems, which can be used to separate the power of the input signal into two output channels with equal or unequal power levels. Conventional SSPP-based power dividers were designed based on the coplanar waveguide (CPW) etched with periodic gradient grooves [12-14], SSPP metal grating splitters with finite thickness [15-18], and some other structures [19-22]. However, most of the power dividers based on the periodic gradient grooves were anti-symmetrical designs, which were adverse to transmission efficiency improvement. Moreover, some SSPP metal grating splitters with finite thickness have also been proposed in [15-18]. The designs divide the signal into two or more different directions. Nevertheless, the fabrication cost was expensive. Additionally, a design based on the lumped element was proposed in [20] and it was not a planar design, which was not benefit for integration. Hence, [21] proposed a high efficiency and planar splitting structure, which was based on the CPW with

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hole arrays etched on its stripline. Nevertheless, all of the above proposed designs were wave splitter, which separate the power of the input signal into two output channels with equal levels and less of them can be used to design a frequency splitter. In [23], a planar frequency splitter experimentally based on SSPPs of planar composite periodic gratings was proposed. However, this design is not conduct to size miniaturization. Therefore, designing a compact planar low cost SSPP-based frequency splitter with high efficiency and good isolation is technically very challenging. Recently, [24] proposed a SSPP waveguide filter based on the CPW etched with semi-hole arrays to achieve the SSPP performance and maybe a good candidate for designing the desired SSPP-based devices.

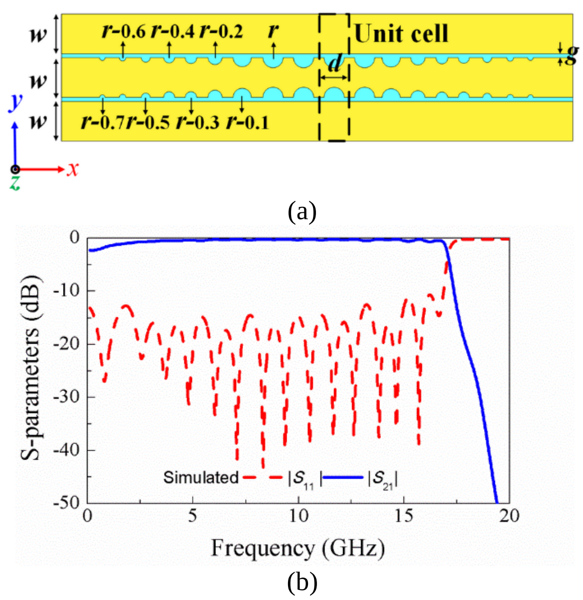


Fig. 1. (a) Configuration of the semi-hole arrays SSPP waveguide, and (b) simulated S-parameters of the semi-hole arrays SSPP waveguide.

In this paper, a frequency splitter based on the semi-hole arrays SSPP-based structure is proposed. The frequency splitter is designed by using the semi-hole arrays etched on the CPW stripline as input signal and splitting the input wave into two output channels with the different cut-off frequencies, which can be controlled by changing the length of unit cell. The operating principle of the proposed frequency splitter is analyzed using dispersion relationships, electric field distributions, and equivalent circuit. Meanwhile, fabricated prototypes are measured and verified our simulated results. The proposed frequency splitter has the following advantages: 1) the transmission efficiency is high; 2) the isolation of the two outputs is good; 3) the cut-off frequency can be easily controlled by changing the corresponding parameters; 4) the design is compact and the fabrication cost is low.

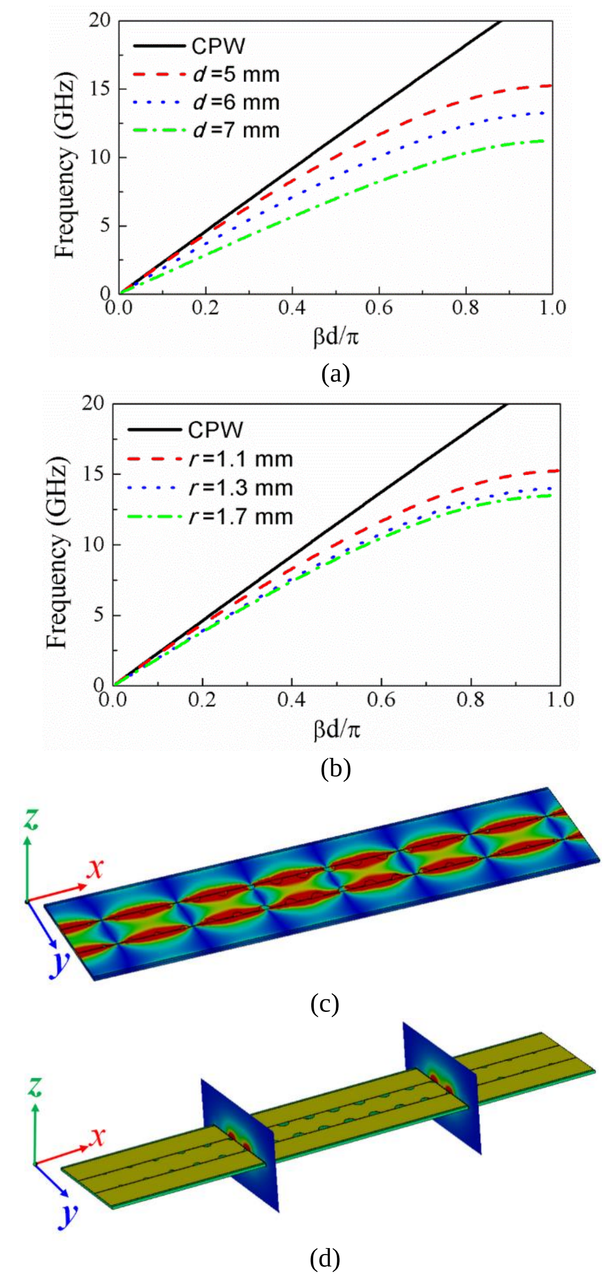
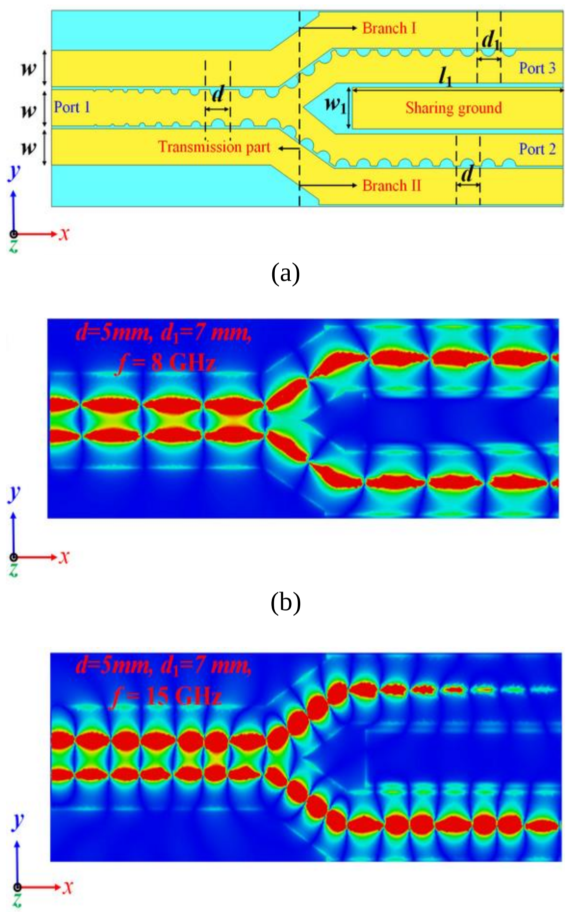


Fig. 2. (a) Dispersion curves with different unit cell length when r = 1.1 mm, (b) dispersion curves with different hole radii when d = 5 mm, (c) electric field distribution on the x–y plane at 8 GHz when d = 5 mm, and (d) magnitudes of energy flows on cross sections at 8 GHz when d = 5 mm.

II. DESIGN CONSIDERATIONS

A. Semi-hole arrays SSPP waveguide

The configuration of the semi-hole arrays SSPP waveguide is sketched in Fig. 1 (a), which is a 50-Ω CPW line etched with periodic semi-hole arrays on the both sides of the middle line. The design is printed on the F4B substrate with a thickness of 0.5 mm, a relative permittivity of 2.65, and a loss tangent of 0.0015. The width and gap of CPW are denoted as w and g, respectively. The unit cell is shown in the dashed frame, its length is marked as d. The detailed designed parameters values are w = 6 mm, g = 0.1 mm, d = 5 mm, and r = 1.1 mm. The simulated $|S_{11}|$ and $|S_{21}|$ of the semi-hole arrays SSPP waveguide are plotted in Fig. 1 (b), it is clear that the design has a cut-off frequency at 16 GHz and the transmission efficiency is very high, which means that the design has transformed quasi-TEM wave to SSPPs (TM) wave.



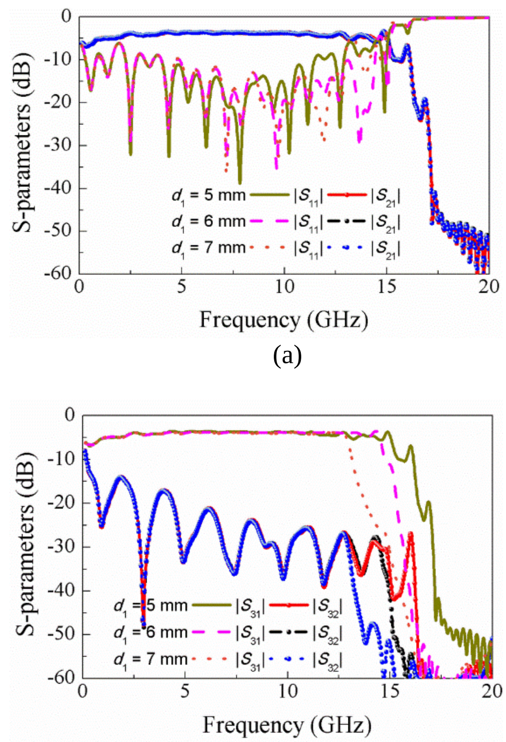
(a)

(b)

(c)

Fig. 3. (a) Structure of the proposed frequency splitter, (b) the simulated electric field distribution on the x-y plane when d=d_1=5 mm at 15 GHz, and (c) the simulated electric field distribution on the x-y plane when d=5 mm, d_1=7 mm at 15 GHz.

In order to further illustrate the design can transform the quasi-TEM wave to SSPPs (TM) wave efficiently, Figs. 2 (a) and (b) present the simulated dispersion curves of the semi-hole arrays SSPP waveguide with different unit cell lengths and hole radii, respectively. It can be clearly seen that the cut-off frequency decreases as the d and r increase. Figures 2 (c) and (d) give the simulated electric field distribution on the x-y plane and the magnitudes of energy flows on cross-sections at 8 GHz when d = 5 mm. From these two figures, we can observe that the EM energy is highly localized within a small region around the slot lines of CPW. Hence, the design can support the SSPPs wave propagates on its surface and the dispersion characteristics can be used to control its cut-off frequency.



(a)

(b)

Fig. 4. Simulated (a) $|S_{11}|$, $|S_{21}|$, and (b) $|S_{31}|$, and $|S_{32}|$ with different d_1 values.

B. The proposed frequency splitter

From the above analysis, we know that the semi-hole arrays SSPP waveguide can support the SSPP mode and have a high transmission efficiency. In order to design a frequency splitter, we split the structure as two branches, as shown in Fig. 3 (a). The transmission part has the same parameter values as the semi-hole arrays SSPP waveguide. The opening angle of the two branches is 60°. The performance of the proposed frequency splitter can be controlled by changing the unit cell length of the branch I (denoted as d_1). From the dispersion curves in Fig. 2 (a), we known that the cut-off frequency are decreases as the unit cell length raises, which means that the cut-off frequency of branch I can be controlled by changing d_1. Figures 3 (b) and (c) give the simulated electric field distributions on the *x*-*y* plane at 8 GHz and 15 GHz when d=5 mm and d_1=7 mm, respectively. It can be seen that the branch I and II have the same energy flow from transmission part to port 2 and 3 at 8 GHz when d=5 mm and d_1=7 mm. However, when the frequency is increases to 15 GHz, the energy cannot propagate from branch I to port 3, because the cut-off frequency of the design is below 15 GHz in this case (as shown in Fig. 2 (a)). Nevertheless, the energy can propagate from branch II to port 2, which means that the proposed design can split the signal as two channels with different cut-off frequency.

To obtain the performance of the proposed frequency splitter, the parametric studies are analyzed using commercial software CST. The S-parameters with different d_1 values are presented in Fig. (4). The highest $|S_{21}|$ and $|S_{31}|$ is up to -3.6 dB. From Fig. 4 (a), it is clear that the $|S_{21}|$ almost has no change with the d_1 changes. Moreover, it can be seen in Fig. 4 (b) that the cut-off frequency of $|S_{31}|$ is decrease with d_1 increase and the transmission efficiency below the cut-off frequency is still high. Furthermore, the isolation between port 2 and 3 is all below -15 dB within the operating frequency band. Based on the above analysis, we know that the proposed frequency splitter can divide the input SSPP waves into two branches with different cut-off frequency and can achieve a good performance.

C. Equivalent circuit of the proposed frequency splitter

To further physically explain the frequency splitter behavior, a simplified *LC* equivalent circuit (neglecting *R* as its value will be negligibly small in case of metals) of the proposed frequency splitter is proposed in Fig. 5. In the equivalent circuit, each conducting line in the design can be modeled as an inductance while any pair of parallel conducting edges is represented by some capacitance values. The values of L_1 and C_1 of CPW feeding part can be derived from [25] and [26] and can be expressed as:

$$L_1 = Z_0 \frac{\sqrt{\varepsilon_{re}}}{c_0} \ , \tag{1}$$

$$C_1 = \frac{L_1}{{Z_0}^2} \ , \tag{2}$$

where Z_0 is the characteristic impedance of the CPW feeding part, ε_{re} is the effective dielectric constant, and c_0 is the velocity of light in frees pace.

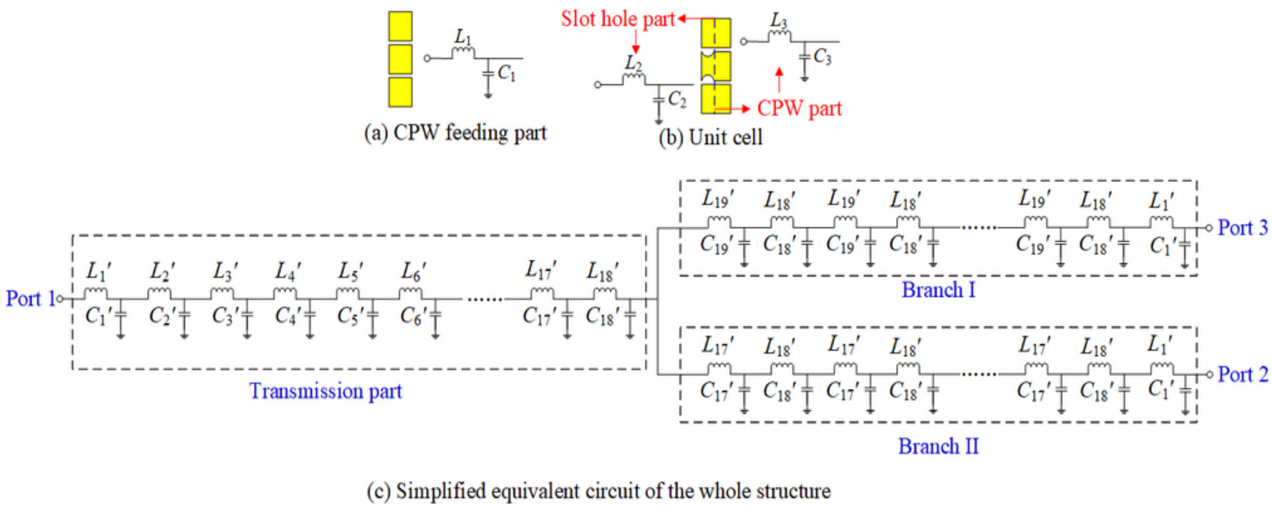


Fig. 5. Simplified equivalent circuits of: (a) CPW feeding part, (b) unit cell, and (c) the whole structure.

In Figs. 5 (a) and (b), the detailed equivalent circuit segmentations of the CPW feeding part and unit cell are presented. The unit cell can be divided as slot hole part and CPW part. If we regard the semi-hole as a uniform rectangular slot, then the slot hole part still can be equivalent as a CPW part. Therefore, based on the above equivalent circuits, a simplified equivalent circuit model for the whole system is synthesized, as shown in Fig. 5 (c), which utilizes the equivalent circuits of the CPW feeding part and unit cell. Additionally, all the odd marks of the *LC* represent the CPW part and the even marks of the *LC* represent the slot hole part. When the unit cell length (d_1) of branch I increases or decreases, the corresponding circuit values of slot hole part of unit cell remains the same and the CPW part changes (as shown in Fig. 5 (b)), which means that the corresponding equivalent circuits of branch I just need to adjust the parameters of L_{19}' and C_{19}' as the unit cell changes. This schematic can be used to understand the performance of the system in circuital terms, and as a useful tool for future designs. According to formulas (1)-(2) and using the advanced design system (ADS) software to optimize the values, the values of the equivalent circuit (when d=d_1=5 mm, the corresponding equivalent circuit parameters $L_{17}'= L_{19}'$ and $C_{17}'= C_{19}'$) are empirically calculated as: $L_1' = 0.379$ nH, $L_2' = 0.821$ nH, $L_3' = 0.33$ nH, $L_4' = 0.893$ nH, $L_5' = 0.314$ nH, $L_6' = 0.839$ nH, $L_7' = 0.298$ nH, $L_8' = 0.89$ nH, $L_9' = 0.282$ nH, $L_{10}' = 0.806$ nH, $L_{11}' = 0.266$ nH, $L_{12}' = 0.558$ nH, $L_{13}' = 0.25$ nH, $L_{14}' = 0.408$ nH, $L_{15}' = 0.233$ nH, $L_{16}' = 0.409$ nH, $L_{17}' = 0.225$ nH, $L_{18}' = 0.204$nH, $L_{19}' = 0.225$ nH, $C_1' = 0.237$ pF, $C_2' = 0.196$ pF, $C_3' = 0.2$ pF, $C_4' = 0.272$ pF, $C_5' = 0.196$ pF, $C_6' = 0.286$ pF, $C_7' = 0.186$ pF, $C_8' = 0.221$ pF, $C_9' = 0.176$ pF, $C_{10}' = 0.19$ pF, $C_{11}' = 0.166$ pF, $C_{12}' = 0.205$ pF, $C_{13}' = 0.156$ pF, $C_{14}' = 0.204$ pF, $C_{15}' = 0.146$ pF, $C_{16}' = 0.343$ pF, $C_{17}' = 0.141$ pF, $C_{18}' = 0.0147$ pF, and $C_{19}' = 0.141$pF.

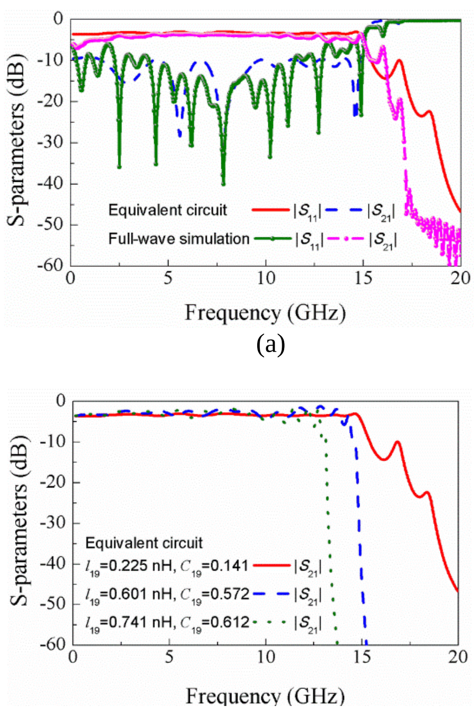


Fig. 6. Simulated S-parameters of the proposed frequency splitter and equivalent circuit model.

The full-wave simulation results are demonstrated together with the scattering parameters of the corresponding simplified equivalent circuit model, as shown in Fig. 6 (a). The results of the full-wave simulation and equivalent circuit (when d=d_1=5 mm, the corresponding equivalent circuit parameters $L_{17}'= L_{19}'$ and $C_{17}'= C_{19}'$) are given and we can see that the simulation results of the equivalent circuit model present the similar trend with the full-wave simulation results, which validate the proposed design exhibits the expected behavior. Moreover, Fig. 6 (b) shows the simulated equivalent circuit results when we change the L_{19}' and C_{19}' values, it is clear that the cut-off frequency of branch I decreases as L_{19}' and C_{19}' increase, which has a good agreement with the physic model (increasing the unit cell length, the cut-off frequency will decrease).

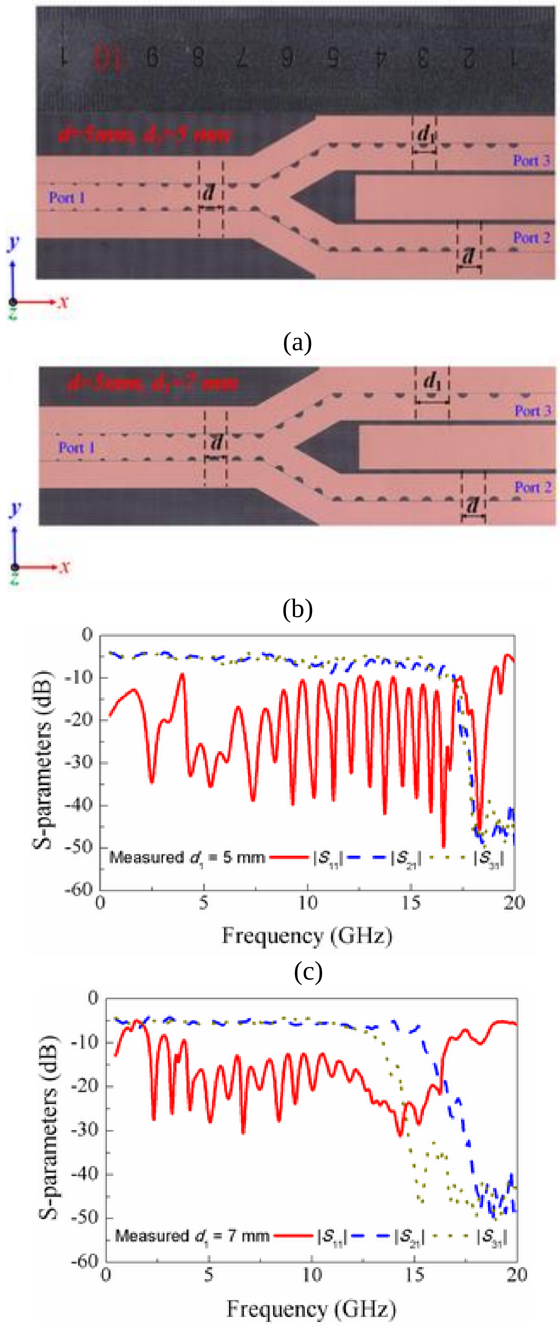


Fig. 7. Photograph of the fabricated frequency splitter when: (a) d_1=5 mm, (b) d_1=7 mm, measured S-parameters of the proposed frequency splitter when (c) d_1=5 mm, and (d) d_1=7 mm.

III. EXPERIMENTAL VERIFICATION

The actual prototypes of the proposed frequency splitter are fabricated on the F4B substrate and measured to characterize its simulated performance, as shown in Fig. 7. The prototypes are fabricated using the standard printed circuit board technologies. The thickness of the fabricated substrate is 0.5 mm, ε_r = 2.65, loss tangent tan δ = 0.0015, and the thickness of metallic strips is 0.035 mm, which can be regarded as a perfect electrical conductor. Figures 7 (c) and (d) show the measured results of the proposed frequency splitter when d_1=5 mm and d_1=7 mm, respectively. It is clear that the measured results are highly consistent with the simulated ones. As shown in Fig. 7 (c), the port 2 and 3 have the same cut-off frequency when d=d_1=5 mm. However, the cut-off frequency of port 3 shift to lower frequency when d_1 increases to 7 mm, shown in Fig. 7 (d). Moreover, the differences between the measured and simulated results at some frequencies and the frequencies have slight difference with the simulated results, which are maybe caused by the SMA soldering and measurement tolerances. As expected, the fabricated prototype can realize a good frequency splitting characteristic and can find potential applications in surface-wave integrated circuits at the microwave frequency band.

IV. CONCLUSION

A frequency splitting SSPP based on the CPW is proposed at microwave frequencies. The frequency splitter is first investigated based on the special semi-hole arrays SSPP waveguide, which is designed by separating the transmission part as two branches. The proposed frequency splitter is investigated by using the dispersion curves and electric field distributions. Prototypes of the proposed frequency splitter with different d_1 have been fabricated and measured to verify the design conception, the measured results agree well with the simulated ones, which show that the proposed design can split the SSPPs with high transmission efficiency, low loss, good isolation, and low cost. The proposed frequency splitting SSPPs features some advantages, which is helpful to design future SSPP devices and find some other applications in microwave frequency band.

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