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Compact Branch-Line Coupler Using Uniplanar Spiral Based CRLH-TL

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Abstract—In this letter, a compact branch-line coupler using a new type of uniplanar composite right/left-handed transmission line (CRLH-TL) is proposed. The transmission line is obtained by etching spiral structure and series meandered capacitive gaps at both ends on the host line. With the aid of lumped element equivalent circuit model and dispersion relations, the CRLH property of the line is studied. By using the proposed structures, the 90-degree phase shift 35.35 ohm and 50 ohm transmission lines are designed for a compact branch-line coupler operating at 1 GHz. Its occupied size is only 32.5% of that of the conventional one. Its uniplanar prototype makes it very useful for wireless communication systems requiring high encapsulation quality.

1. INTRODUCTION

Microstrip branch-line couplers, which offer equal amplitude and 90-degree phase shift between two out-ports, have been widely used in microwave circuits and systems, such as adaptive antenna arrays, balanced mixers, balanced amplifiers, power dividing network [1]. However, the size of conventional branch-line couplers is too large at lower frequency for practical use. Various approaches for branch-line coupler miniaturization can be found in recent research works [2–8]. The slow-wave structure is an effective way for size reduction. The mechanism of the slow-wave propagation is to separately store the electric and magnetic energies as much as possible in the guided-wave media [2–4], which can decrease phase velocity. Using artificial transmission lines is another approach for size reduction [5, 6]. In [5], multiple shunted open stubs have been utilized to replace four quarter-wavelength transmission lines of the conventional branch-line coupler for miniaturization, which has a size reduction about 54%. In [6], a dual-transmission line has been proposed for 63.9% size reduction. Besides, the fractal and meandered geometry can also reduce the branch-line coupler size [7, 8]. However, these two techniques are not suitable for a low impedance line and not easy to model their geometries.

In recent years, the concept of composite right/left handed transmission line (CRLH TL) has been extensively applied to develop compact coupler [9–12]. In these references, CRLH TLs were successfully used for compact coupler design. However, the existence of via holes, defected ground structures (DGS) or lumped elements in these CRLH TLs limits its practical use. In this letter, a new uniplanar CRLH-TL is proposed for compact branch-line coupler design. 35 ohm and 50 ohm CRLH-TLs with 90-degree phase shift are designed using the proposed structure. By replacing the four quarter-wavelength transmission lines of the conventional branch-line coupler with them, a new compact branch-line coupler operating at 1 GHz is synthesized. Both the simulated and measured results show that good performance is obtained. The designed coupler only occupies 32.5% of that of conventional one. Additionally, this compact prototype avoids introducing via holes, DGS, and lumped elements, making it very useful for wireless communication systems that require high encapsulation quality.

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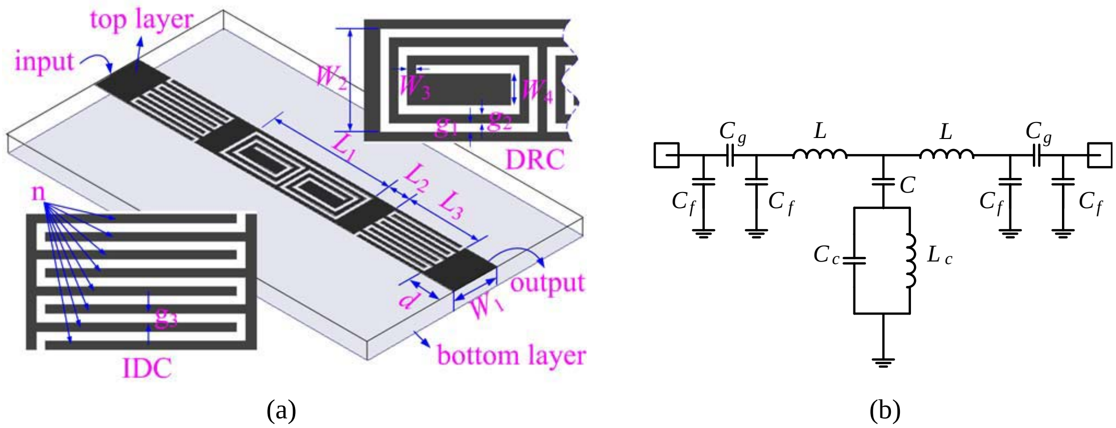


Figure 1. Proposed CRLH TL. (a) Distributed structure. (b) Equivalent circuit model.

2. PROPOSED SPIRAL BASED CRLH-TL

The prototype of the novel uniplanar spiral-based CRLH-TL is shown in Figure 1(a). It is seen that a symmetrical spiral structure is etched on the strip line, and two series meandered gaps are used at both sides for enhancing the coupling between the spiral structure and host line. In the proposed CRLH-TL, both the spiral structure and series meandered gaps are embedded into the conventional 50 ohm microstrip line, which ensures compact transversal dimension of the CRLH-TL.

Figure 1(b) exhibits a loss-less lumped element equivalent circuit model of the CRLH-TL. In this model, L represents the host line inductance, and C_g models the capacitance of series meander gaps. Here, the fringing capacitance C_f introduced by the series gap must be taken into consideration for describing the structures accurately. The etched spiral structure is described by means of a parallel tank formed by C_c and L_c, and the capacitance C accounts for the coupling between the host line and the etched spiral structure. Such a circuit model for this type of CRLH-TL was already reported in [13].

By applying the periodic boundary conditions related to the Bloch-Floquet theory, the dispersion relation β and characteristic impedance Z_0 of the proposed CRLH-TL based on the lumped element equivalent circuit model can be obtained, according to [14]:

$$\varphi = \beta l = \cos^{-1}\left[1 + Z_s(j\omega)\, Y_p(j\omega)\right] \tag{1}$$

$$Z_0 = \sqrt{Z_s(j\omega)\left[Z_s(j\omega) + \frac{2}{Y_p(j\omega)}\right]} \tag{2}$$

where l is the length of the unit cell, and $Z_s(j\omega)$ and $Y_p(j\omega)$ represent the series impedance and shunt admittance, respectively.

$$Z_s(j\omega) = j\left(\omega L - \frac{1}{\omega C_g}\right) \tag{3}$$

$$Y_p(j\omega) = j\omega 4C_f + \left[j\omega C // \frac{1}{j\omega L_c // \frac{1}{j\omega C_c}}\right] = j\omega 4C_f + \frac{j\omega C\left(1 - \omega^2 L_c C_c\right)}{1 - \omega^2 L_c\left(C_c + C\right)} \tag{4}$$

Therefore, the dispersion relation β and characteristic impedance Z_0 can be obtained by inserting (3) and (4) into (1) and (2).

According to Eq. (4), a transmission zero occurs by forcing the denominator to be zero, namely,

$$f_z = \frac{1}{2\pi\sqrt{L_c(C_c + C)}} \tag{5}$$

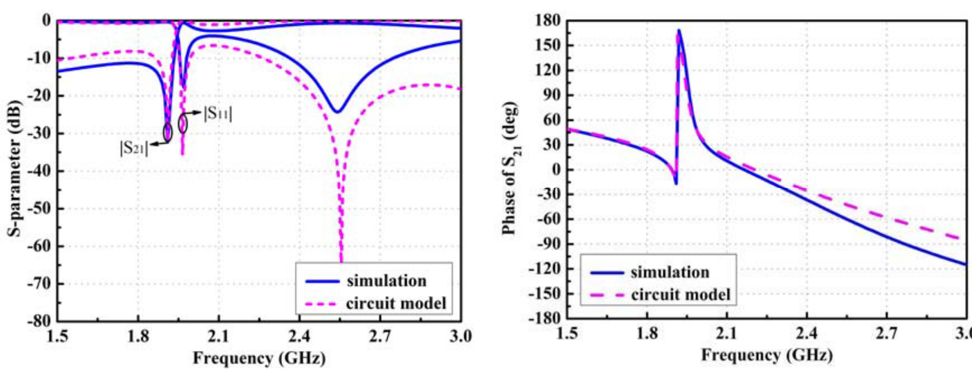
The lower cutoff frequency f_s of the RH band and the upper cutoff frequency f_p of the LH band can be attained by forcing $Z_s(j\omega)$ and $Y_p(j\omega)$ to be zero, respectively.

$$f_s = \frac{1}{2\pi\sqrt{LC_g}} \tag{6}$$

$$f_p = \frac{\sqrt{4C_f + C}}{2\pi\sqrt{4C_f L_c(C_c + C) + CL_cC_c}} \tag{7}$$

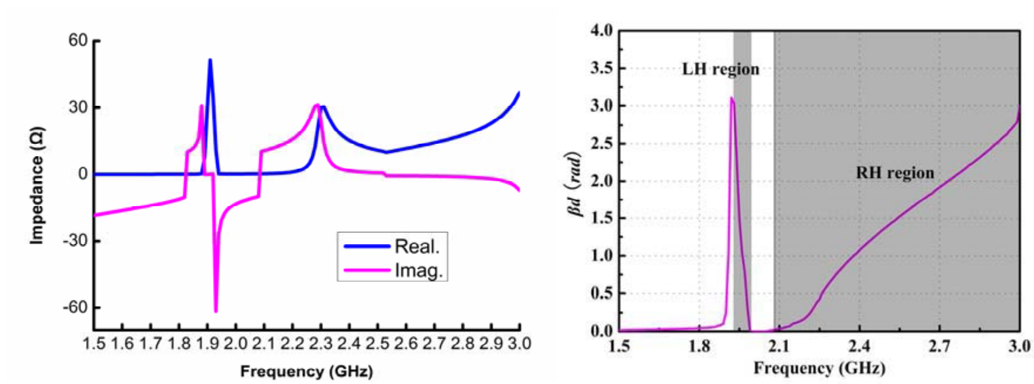
Here, Eqs. (6) and (7) are tenable on the assumption $f_p < f_s$, and RH and LH bands should transform as $f_p > f_s$. Under the balanced condition, namely $f_p = f_s$, there is no gap between the LH and RH bands.

Figure 2 depicts the frequency response of the proposed line obtained by the HFSS and the electrical simulation (circuit model) through the Ansoft Serenade, respectively. The structure is designed on an F4B-2 substrate with a relative dielectric constant 2.65 and thickness of 1.5 mm, and the physical dimensions of this line are $W_1 = 4.05$ mm, $W_2 = 3.45$ mm, $W_3 = 0.3$ mm, $W_4 = 1.05$ mm, $d = 33.3$ mm, $L_1 = 10.8$ mm, $L_2 = 2$ mm, $L_3 = 6.25$ mm, $g_1 = 0.3$ mm, $g_2 = 0.3$ mm, $g_3 = 0.27$ mm, $n = 8$. As can be observed, the S-parameters attained by the HFSS are in good agreement with the Serenade results. The phenomenon of phase lead appears at the pass band from 1.92 GHz to 1.98 GHz, which proves that it is a LH band. Additionally, a transmission zero at 1.91 GHz (lower than LH band) provides a sharp transition. The values of the extracted circuit parameters are as follows: $C_g = 0.68$ pF, $C_f = 0.54$ pF, $C = 1.18$ pF, $C_c = 8.43$ pF, $L = 6.91$ nH, $L_c = 0.72$ nH. By substituting these values for variables in the above expressions, f_z, f_s and f_p can also be obtained. The calculated results agree well with the simulated ones, which validates the correctness of above analysis.



(a) (b)

Figure 2. Frequency responses of proposed CRLH TL: (a) S-parameter, (b) phase of S_{21}.



(a) (b)

Figure 3. Representation of (a) Bloch impedance and (b) dispersion relation of the proposed CRLH TL cell.

Also, the dispersion diagram and characteristic impedance can be calculated from Equations (1) and (2). The calculated Bloch impedance and dispersion relation are shown in Figure 3. It can be observed that a small band gap actually exists between the LH and RH regions.

3. BRANCH-LINE COUPLER DESIGN

3.1. Design of 35 ohm and 50 ohm Transmission Lines

To demonstrate the possibility of employing proposed spiral-based CRLH-TL on compact microwave devices, a branch-line coupler operating at 1 GHz has been designed. As reported in [1], 50 ohm and 35 ohm transmission lines with quarter wavelength phase-shift should be initially designed for a branch-line coupler. Here, a simple principle is used for the design of these two transmission lines. In HFSS simulation, two lumped ports with required characteristic impedance are set at both sides of one transmission line. Good impedance matching between the transmission line and both lumped ports results in less return loss. So, achieving satisfactory return loss is a significant criterion for obtaining necessary characteristic impedance of the proposed transmission line. For designing a 50 ohm transmission line, W_1 is fixed at 4.05 mm which is consistent with the width of the conventional 50 ohm microstrip line, and other parameters are adjusted. In the same way, a 35 ohm transmission line can also be designed. In Table 1, corresponding geometrical parameters of the designed 50 ohm and 35 ohm microstrip lines are given. The simulated results are shown in Figure 4. It can be observed that good transmission properties and 90-degree phase shift are obtained at 1 GHz. Thus, 50 ohm and 35 ohm transmission lines needed by branch-line coupler are obtained. Additionally, the total length of the 50 ohm and 35 ohm transmission lines are 33.3 mm and 24.25 mm, which are shorter than the normal quarter wavelength transmission line (about 50.8 mm and 49.8 mm) on the same substrate.

3.2. Branch-Line Coupler Designed, Fabricated and Measured

Based on the above analysis and for verification, a compact branch-line coupler operating at 1 GHz can be designed by using the proposed 50 ohm and 35 ohm spiral-based CRLH-TLs because of their shorter length. In this integration process, a mutual coupling between transmission lines should be considered and the further optimization is necessary. Here, the length of the feed lines of each branch (d) is

Table 1. Structure parameters for 90-degree phase shift 50 Ω and 35 Ω CRLH TLs (Unit: mm).

Parameters	W_1	W_2	W_3	W_4	d	L_1	L_2	L_3	g_1	g_2	g_3	n
50 ohm	4.05	3.75	2.15	1.35	3.1	11.1	0.15	7.85	0.15	0.15	0.15	14
35 ohm	6.75	6.45	0.15	1.55	2.5	6.45	0.15	6.25	0.15	0.15	0.15	23

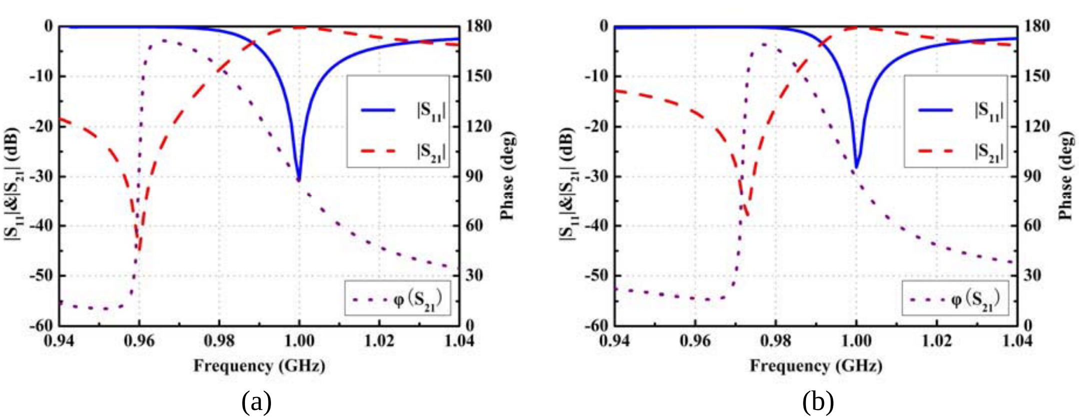


Figure 4. Frequency responses of CRLH-TLs operating at 1 GHz: (a) 50 ohm, (b) 35 ohm.

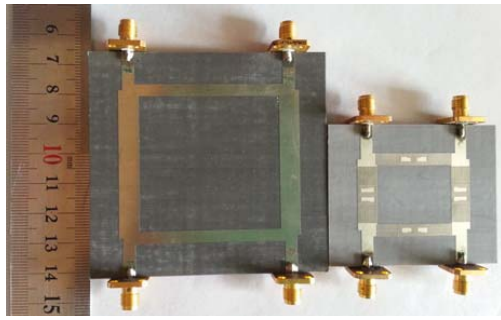


Figure 5. The layout of the proposed branch coupler.

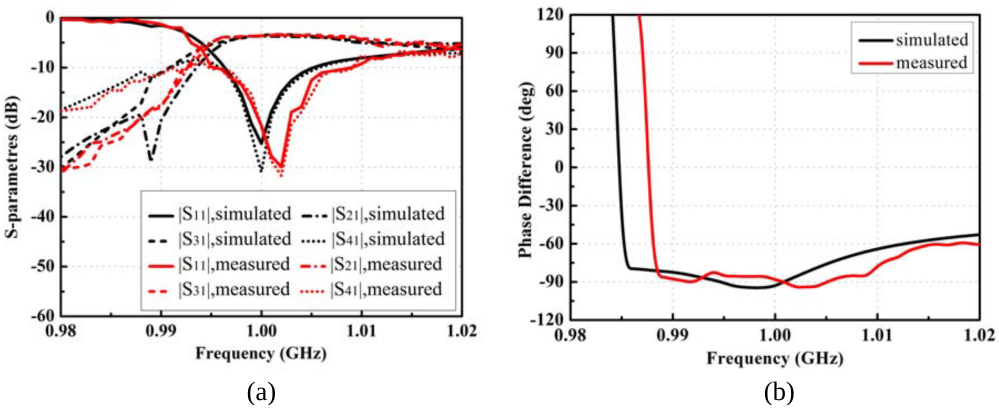


Figure 6. Simulated and measured results of the proposed branch-line coupler: (a) S-parameters, (b) phase differences between the output ports.

optimized, and other parameters are identical to those of the proposed transmission lines in Section 3.1. Normally, d is expected to be as small as possible to get compact dimension without deteriorating the performance. Based on this principle, d for the 50 ohm and 35 ohm transmission lines are obtained. Then, the designed branch-line coupler is fabricated and measured. Figure 5 shows photographs of the proposed and conventional branch-line couplers. Measurement was carried out on an Anritsu ME7808A vector network analyzer.

Figure 6 shows the simulated and measured S-parameters and phase differences between two output ports of the proposed branch-line coupler. The measured and simulated results agree well with each other. As can be seen from Figure 6, the centre frequency of the branch-line couplers is 1.002 GHz. The reflection coefficient of port 1 ($|S_{11}|$) is lower than -28 dB, and the isolation $|S_{41}|$ is lower than -30 dB at 1.002 GHz. At the centre frequency, the measured transmission coefficients $|S_{21}|$ and $|S_{31}|$ are 3.36 dB and 3.53 dB, respectively. And the 3 dB bandwidth of the insertion losses ranges from 0.994 GHz to 1.016 GHz. According to a criterion of $\pm 5^\circ$ around 90° phase difference, the corresponding frequency ranges from 0.995 GHz to 1.009 GHz.

The effective dimensions of the proposed and conventional branch-line coupler operating at 1 GHz are $28.4 \times 39.75\,\text{mm}^2$ and $57.1 \times 61\,\text{mm}^2$, respectively. It means that the proposed branch-line coupler can effectively reduce the occupied area to 32.5% of the conventional one at 1 GHz. The coupler is miniaturized because the total lengths of CRLH-TLs are shorter than traditional quarter-wavelength transmission-lines. As can be seen from Figure 5, the proposed branch-line coupler without any lumped elements, via-holes and defected ground structures (DGS) can be fabricated easily. In addition, the characteristics of other published CRLH Branch-line Couplers [15, 16] are tabulated in Table 2 and compared to the proposed one. The proposed compact CRLH Branch-line Coupler has a more considerable size reduction and easily fabricated configuration, though the bandwidth is not broad enough.

Table 2. Comparison between various CRLH branch-line coupler.

	Frequency bandwidth	Size reduction	Configuration
[15]	1.7%	55.7%	No-via, uniplanar
[16]	3%	56.7%	No-via, DGS
This work	1.8%	67.5%	No-via, uniplanar

4. CONCLUSION

In this paper, a compact branch-line coupler based on spiral-based CRLH-TLs is proposed and implemented. Firstly, the properties of the spiral-based CRLH-TL are investigated deeply. Then, the 35 ohm and 50 ohm transmission lines are designed for integrating a branch-line coupler. The results indicate that the designed transmission lines have good transmission properties and 90-degree phase shift at the specific frequencies. Thanks to the small physical length of the spiral-based CRLH-TLs, the area of the proposed branch-line coupler is only 32.5% of the conventional one at the same frequency. Besides, the proposed coupler can be easily fabricated with a standard printed circuit board process because no via holes, DGS or lumped elements are introduced. However, the proposed compact microstrip branch-line coupler is suitable for narrowband systems only.

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