Design of Dual-Band Branch-Line Coupler Based on Shunt Open-Circuit DCRLH Cells

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Abstract. *In this article, the shunt open-circuit dual composite right/left-handed (DCRLH) cell is initially proposed and one dual-band branch-line coupler based on the proposed cells is designed. It is found that, compared with DCRLH cell, the frequency selectivity, matching condition and adjustment range of the shunt open-circuit DCRLH cell improve greatly. Moreover, the shunt open-circuit DCRLH cell exhibits two adjustable frequency points with -90degrees phase shift within its first two passbands. In order to explore this exotic property effectively, the influence of the primary geometrical parameter is investigated through parametric analysis. Thus, one dual-band branch-line coupler based on the shunt open-circuit DCRLH cells is designed. Both simulated and measured results indicate that comparative performance is achieved. Different from part of previous dual-band branch line couplers, for the proposed coupler, the signs of phase difference of two output ports within the two operating frequency bands are identical with each other. This branch-line coupler is quite suitable for the application which is sensitive to the variation of phase difference and its effective area is compact.*

Keywords

Dual composite right/left-handed cell, shunt open-circuit DCRLH cell, dual-band, branch-line coupler.

1. Introduction

In modern communication handsets, the microstrip dual-band components are utilized extensively. Microstrip element has obvious advantages of easy fabrication and low-weight and realization of two operating bands in one prototype helps to miniaturize dimension and reduce cost. One of these components, the dual-band microstrip branch-line coupler is the target of this article. Various methods have been introduced to design dual-band microstrip branch-line coupler. One example is realized by making the lengths of parallel lines and branch lines unequal and adding open-circuit stub in the center of parallel lines [1]. Whereas for this coupler, the signs of phase difference between two output ports within the two operating frequency bands are opposite to each other. This property is not suitable for the applications which are sensitive to the sign change in phase difference. In [2], the open-circuit stubs with different characteristic impedance and electrical length are added in the centers of both parallel lines and branch lines to design the dual-band branch-line coupler. But, the abovementioned problem of opposite signs of phase difference still exists. Recently, one prototype is achieved through inserting transmission-line sections into all the ports of conventional branch-line coupler with modified branch parameters[3]. For this coupler, the phase differences within the two frequency bands are identical, but the port extension surely enlarges the effective area greatly. With the development of composite right/left-handed (CRLH) transmission line, its inherent dual-band property, namely the left-handed passband in lower passband and right-handed passband in higher passband is explored to design the dual-band branch-line couplers [4], [5]. One of these couplers is designed on the basis of CRLH cell realized by lumped components. Another one is realized by CRLH cell based on the complementary split ring resonator (CSRR). For the this kind of dual-band branch-line coupler, the frequency point with +90 degrees phase shift in left-handed passband and the frequency points with -90 degrees in right-handed passband are utilized. Thus, the signs of phase difference between two output ports within two operating frequency bands are opposite to each other.

In this article, the shunt open-circuit DCRLH cell which is the improved version of DCRLH is proposed to design dual-band microstrip branch-line coupler. DCRLH is the dual version of CRLH and DCRLH cell has the right-handed passband in lower frequency band and left-handed passband in higher passband. It is demonstrated that the matching condition, frequency selectivity and adjustment range of the shunt open-circuit DCRLH cell are all superior to those of DCRLH cell. What is more important, there are two adjustable frequency points both with -90 degrees phase shift within the first two passbands. This property is explored to design the dual-band branch-line coupler. For the proposed coupler, the primary merit is the identical signs of phase difference between two output ports within the two operating frequency bands. Moreover, the effective area of the proposed coupler is approximately equal to that of the conventional prototype.

2. Limitation of the Microstrip DCRLH Cell

The dual composite right/left handed (DCRLH) cell is the dual version of composite right/left handed (CRLH) cell which plays an extremely important role in the metamaterials research. The concept of DCRLH and its equivalent circuit shown in Fig. 1 were initially proposed in 2006[6]. DCRLH exhibits the left-handed passband in higher frequency band and the right-handed passband in lower frequency band, which is opposite to CRLH. Several realization versions of DCRLH have been proposed [7]-[12]. Specially, the published microstrip realization is depicted in Fig. 2(a) [11], [12]. In this prototype, C_L and L_R are realized by one interdigital capacitor and one narrow microstrip line parallel to the given interdigital capacitor, respectively. Meanwhile, C_R and L_L are realized by rectangular patch and shunt narrow microstrip line, respectively. For simplicity, only single shunt part is included in Fig. 2(a) and DlcW2 = DlcW1, DlcL2 = DlcL1 - 0.2 mm, DrcL1 = DrcL2 are kept throughout. In this article, the substrate with relative dielectric constant of 2.2 and thickness of 1.5 mm is utilized in both simulation and fabrication.

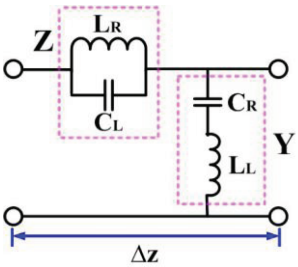


Fig. 1. Equivalent circuit model of DCRLH.

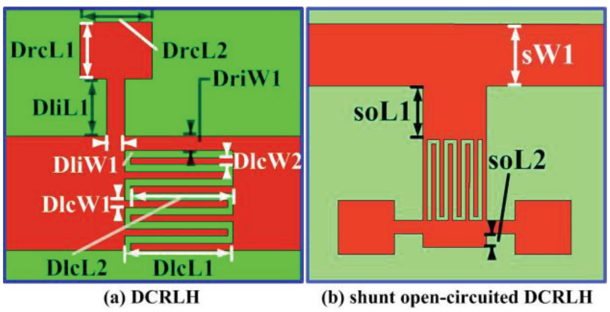


Fig. 2. (a) DCRLH cell, (b) shunt open-circuit DCRLH cell.

In the published investigation, the property of the given microstrip DCRLH cell has not been explored thoroughly and individually. In this article, it is found that the right-handed passband is only sensitive to two parameters, DliW1 and DliL1. The cutoff frequency of right-handed passband moves downward with the decrease of DliW1 while the given cutoff frequency moves downward with the increase of DliL1. In practice, the given cutoff frequency is difficult to move downward further when DliW1 is close to 0.1 mm which is our minimized achievable fabrication tolerance. On the other hand, the effective area of the proposed DCRLH cell will enlarge to great extent with the increase of DliL1. Thus, the design arbitrariness is deteriorated due to above limitations.

3. Design of the Shunt Open-Circuit DCRLH Cell

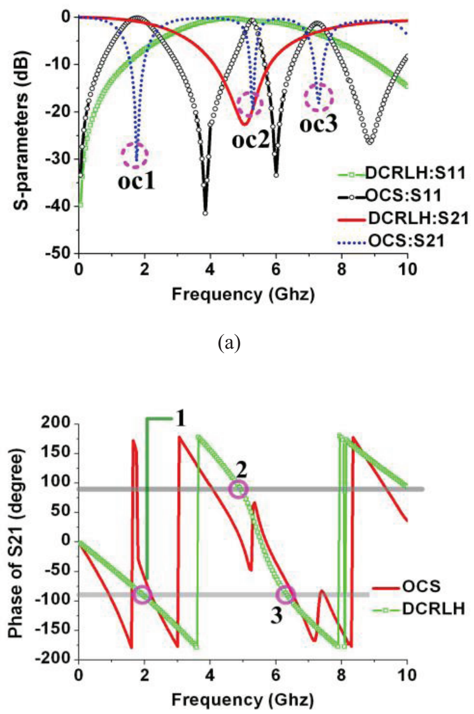
3.1 Proposition of the Shunt Open-Circuit DCRLH Cell

To solve the above limitations, one improved version of DCRLH, the shunt open-circuit DCRLH cell is proposed and its geometry is shown in Fig. 2(b). According to the transmission line theory, the input impedance of the conventional open-circuit transmission line can be expressed as (1):

$$Z_{in}^{oc}(d) = -jZ_0 ctg(\beta d) \tag{1}$$

where d denotes the physical length of the given transmission line, the superscript '*oc*' is the abbreviation of open-circuit and the subscript '*in*' is the abbreviation of input. When $d = \lambda/4$, the input impedance is equal to zero where λ is the wavelength at the frequency of f_0. Thus, for $\lambda/4$ open-circuit stub, there is one transmission zero at f_0. Based on the same operating principle, it is expected that the shunt open-circuit DCRLH cell also exhibit bandstop property at the frequency with -90 degrees phase shift within the right-handed passband of corresponding DCRLH cell. To demonstrate the above expectation, DCRLH cell and shunt open-circuit DCRLH cell are compared in two cases and the results are depicted in Fig. 3 and Fig. 4, respectively. In simulation with the help of HFSS, soL1 = 6 mm, soL2 = 1.5 mm are kept constant. In case 1, DrcL1 = 5.0 mm, DliL1 = 4.0 mm, DliW1 = 2.5 mm, DlcW1 = 0.3 mm, DriW1 = 0.3mm, DlcL1 = 5mm, DlcL2 = 4.8 mm. In case 2, DliW1 = 1 mm, DlcL1 = 5.1 mm, DlcL2 = 4.9 mm and the other parameters are identical with the ones in case 1. In both Fig. 3 and Fig. 4, 'OCS' denotes the shunt open-circuit DCRLH cell and the phase shift curves are all wrapped.

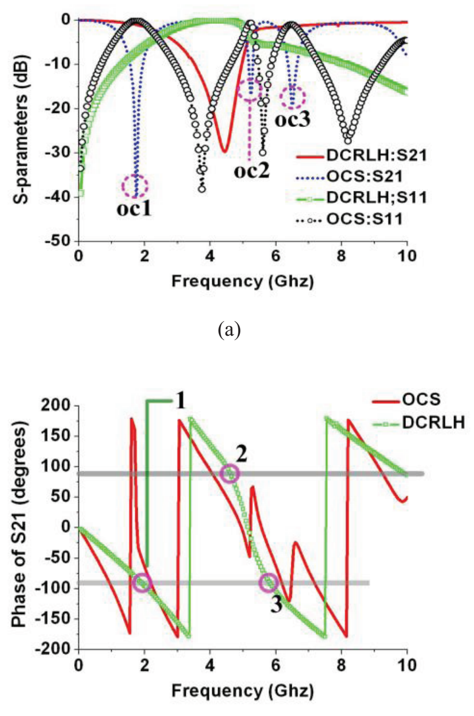
As shown in above two figures, within the given frequency band, the shunt open-circuit DCRLH cell exhibits three transmission zeros denoted as 'oc1', 'oc2', 'oc2'. Obviously, this cell is of great potential to design multi-band components. In both cases, the transmission zeros approximately corresponds to the frequency points (which are denoted as '1', '2', '3'.) with ± 90 degrees phase shift for DCRLH cell. With the increase of frequency, the error between the transmission zeros and the given frequency points become more and more obvious. The reason may be that the electrical length of the microstrip line which connects DCRLH cell and the main transmission line cannot be ignored when the frequency becomes high enough. Thus, it is demonstrated that our expectation is right and effective. It means that the passband within lower frequency band than corresponding



(a)

(b)

Fig. 3. Comparison results of (a) S-parameters and (b) phase of S21 in case 1.



(a)

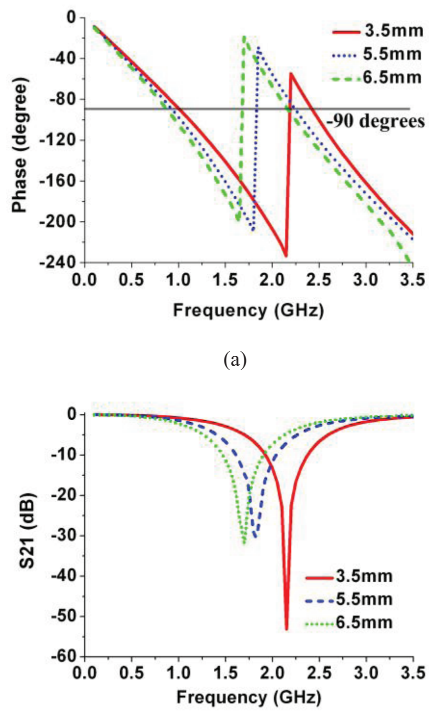
(b)

Fig. 4. Comparison results of (a) S-parameters and (b) phase of S21 in case 2.

DCRLH cell can be achieved utilizing the shunt open-circuit DCRLH cell. Thus, the design freedom is enhanced greatly. On the other hand, the matching condition and frequency selectivity of passbands and stopbands of the shunt open-circuit DCRLH cell are both superior to the ones of DCRLH cell. It should be noted that these excellent performances are all achieved without any optimization. What is more important, there are two frequency points with -90 degrees for the shunt open-circuit DCRLH within the right-handed passband of corresponding DCRLH cell, as shown in Fig. 3(b) and Fig. 4(b). Moreover, these two frequency points both fall in the passbands. Due to the nonlinear phase shift response of DCRLH cell, these two frequency points can be adjusted. It is suitable to design the dual-band components requiring the quadrature phase shift.

3.2 Influence of the Primary Geometrical Parameter

Next, the exotic phase property of the shunt open-circuit DCRLH cell is focused on and the adjustment rule on the given two frequency points with -90 degrees phase shift is investigated further. Through parametric analysis, it is found that one geometrical parameter; DrcL1 is suitable to control the two frequency points. The given results are depicted in Fig. 5. It is seen that the distance between the two frequency points is enlarged with the decrease of DrcL1. This provides a guideline to design the special components.



(a)

(b)

Fig. 5. Effect of DrcL1 on the properties of the shunt open-circuit DCRLH cell.

4. Design and Fabrication of the Dual-Band Branch-Line Coupler

In this section, one dual-band branch-line coupler is designed utilizing the two frequency points with -90 degrees phase shift within the first two passbands of the shunt open-circuit DCRLH cell. The proposed dual-band branch-line coupler is depicted in Fig. 6.

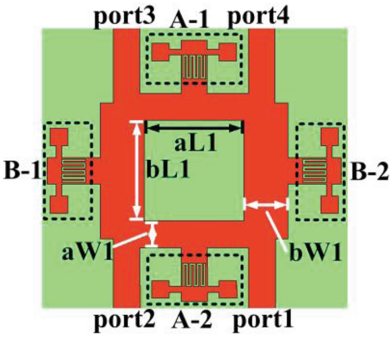
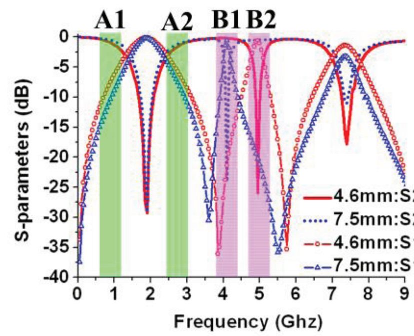
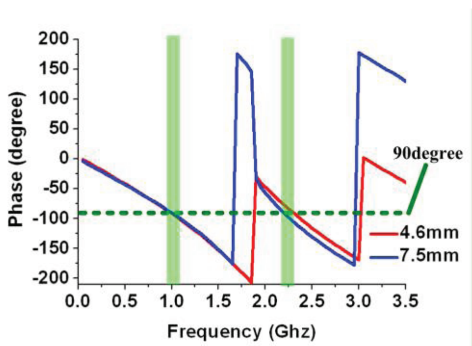


Fig. 6. Configuration of the proposed dual-band branch-line coupler.

It is necessary to investigate the effect of different widths of main transmission line on the properties of the shunt open-circuit DCRLH cell and the simulated results are shown in Fig. 7. The parameters are listed as following: DrcL1 = 5. 0mm, DliL1 = 4.0 mm, DliW1 = 2.0 mm, DlcW1 = 0.3 mm, DriW1 = 0.3 mm, DlcL1 = 5.3 mm, DlcL2 = 5. 0mm, soL1 = 2.5 mm, soL2 = 0.5mm and the physical length of the main transmission lines is 30 mm.



(a)



(b)

Fig. 7. Effects of different widths of main transmission line on (a) S-parameters (b) phase of S21.

As shown in Fig. 7, it is seen that the width difference of main transmission line influence both S-parameters and phase-shift property to extremely small extent. Thus, as the shunt parts, DCRLH cells in proposed coupler all have the identical geometrical parameters, which can facilitate the optimization process greatly. In the design procedure, only the geometrical parameters, aL1 and bL1 shown in Fig. 6 are included in the optimization process. Consequently, aL1 = 26 mm and bL1 = 28.5 mm are chosen. After optimization, the proposed branch-line coupler is fabricated and measured. The simulated and measured results are shown in Fig. 8 and Fig. 9 while the photograph of the fabricated prototype is shown in Fig. 10. The vector network analyzer with two ports (Agilent N5232A) was utilized in measurement. The idle ports were loaded with 50 Ω load in the measurement process.

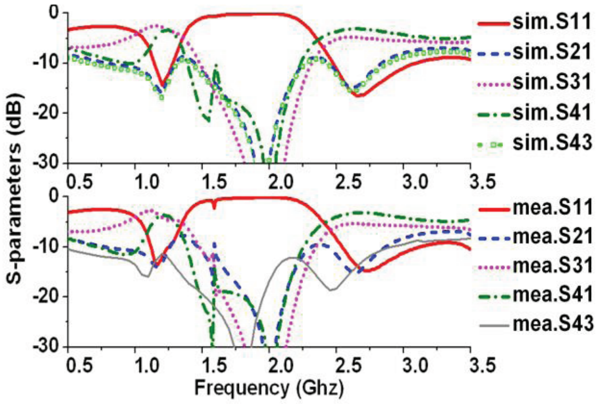


Fig. 8. Simulated and measured S-parameters.

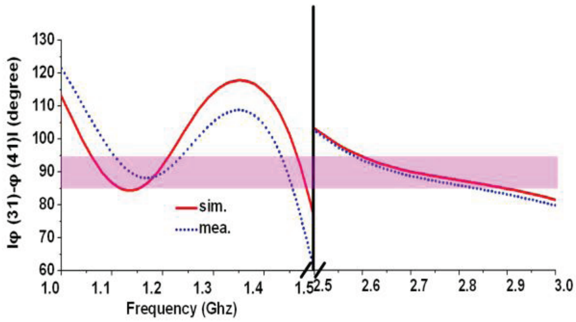


Fig. 9. Simulated and measured phase difference between port3 and port4.

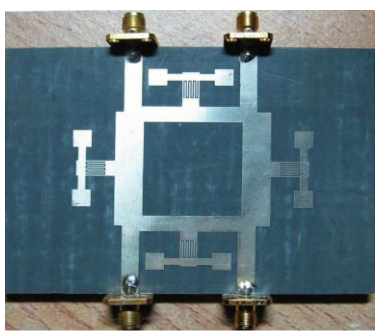


Fig. 10. Photograph of the fabricated prototype.

As depicted in the figures above, the simulated and measured results roughly agree well and the discrepancy may be due to the tolerance in fabrication. Firstly, the measured S_{11} is better than -10 dB from 1.14 GHz to 1.27 GHz in the lower frequency band. The measured $|S_{31} - 3| \leq 1$ dB and $|S_{41} - 3| \leq 1$ dB are both satisfied from 1.18 GHz to 1.24 GHz while S_{43} is better than -10 dB from 0.68 GHz to 1.31 GHz. Meanwhile, $||\varphi(S_{31}) - \varphi(S_{41})| \text{-}90°| \leq 5°$ is satisfied from 1.09 GHz to 1.23 GHz. Secondly, according to the measured results, S_{11} is better than -10 dB from 2.47 GHz to 3.06 GHz in the higher frequency band. $|S_{31} - 3| \leq 1$ dB and $|S_{41} - 3| \leq 1$ dB are both satisfied from 2.52 GHz to 2.74 GHz while S_{43} is better than -10 dB from 2.43 GHz to 2.87 GHz. Moreover, $||\varphi(S_{31}) - \varphi(S_{41})| \text{-}90°| \leq 5°$ is satisfied from 2.58 GHz to 2.83 GHz. The conventional dual-band branch-line coupler based on CRLH utilizes two frequency points with +90 degrees and -90 degrees, respectively. Different from the dual-band branch-line coupler based on CRLH, the proposed dual-band branch-line coupler explores two frequency points with both -90 degrees. Thus, the sign of the phase difference between two output ports within the two operating frequency bands are identical which is quite suitable for the applications sensitive to sudden change in phase difference. Additionally, the length of the shunt open-circuit DCRLH cell is not necessary to set the quarter of the wavelength at the given frequency point and, thus, miniaturization can be achieved. The above advantage in area is deteriorated due to the shunt parts. At last, the effective area of the fabricated prototype is 63.8 mm × 60.3 mm (0.245 $\lambda \times$ 0.231 λ, where λ is free-space wavelength at center frequency, 1.15 GHz of lower passband). The given effective area is approximately equal to the one of the conventional microstrip branch-line coupler.

5. Conclusions

In this article, we propose one improved version of DCRLH cell, the shunt open-circuit DCRLH cell. Compared with DCRLH cell, the matching condition, frequency selectivity and adjustment freedom of the improved version are all superior. Moreover, two frequency points both with -90degrees phase shift can be achieved within the first two passbands, respectively. This property is the key to design the proposed dual-band branch-line coupler whose signs of phase difference within the two operating frequency bands are identical with each other. For most dual-band branch-line coupler proposed previously, the abovementioned signs are opposite which is not applicable in the conditions with strict phase difference requirement. On the other hand, the effective area of the proposed coupler is compact and is approximately equal to that of the conventional microstrip branch-line coupler.

Acknowledgements

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