Design of new compact branch-line coupler using coupled line dual composite right/left-handed unit cells

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In this paper, new proposed compact 3dB Branch-Line Coupler (BLC) is designed and implemented using coupled line unit cells, that have the same properties as Dual Composite Right/Left-Handed (D-CRLH) unit cells. The Printed Circuit Board (PCB) technique is used for the fabrication without using lumped components or via holes. The size of the proposed BLC occupies only 52 % of the area of the conventional design to operate at 1.8 GHz. Two different simulators, CST Electromagnetic EM simulator, and ADS circuit simulator are used to simulate the proposed structure. The structure with optimum parameters is fabricated and the comparison between the measured and the simulation results shows very good agreement.

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Keywords: Branch-line Coupler BLC, D-CRLH, CST, ADS

1. Introduction

Branch-Line Coupler (BLC) is a popular passive microwave device used in many applications such as power divider, power combiner, balanced amplifier, and mixers. BLC has four ports, and four transmission lines, as shown in Fig. 1. Two horizontal parallel transmission lines TLs each with characteristic impedance equals to $Z_o/\sqrt{2}$, connected with another two vertical parallel TLs each with a characteristic impedance equals to Z_o. Each arm of these TLs has a length equals to λ/4. This length becomes larger in low frequency applications, and the conventional BLC occupies large dimensions [1].

Many studies have been presented to reduce the size of the BLC, and they can be classified into two main categories: classical and new techniques. In the classical ones, the size reduction can be done using lumped components, meandering transmission lines, or using stepped impedance [2]. The new techniques become useful since the introduction of the concept of the Composite Right/Left-Handed transmission line (CRLH-TL) in [3]. The door becomes open to design more compact passive microwave components. In [4], an arbitrary dual bands BLC was designed using lumped components and short stubs. In [5] and [6], BLCs were designed to operate in dual and triple bands respectively. Both structures are suitable only for phase sensitive applications, since they have high sensitivity to phase changing. Another compact size BLC was presented in [7], using D-CRLH to operate at quad bands.

In this paper, the D-CRLH unit cell that is presented in [8,9] is used to design and implement a compact BLC with very easy and simple printed circuit board PCB planner fabrication techniques, without any via holes, ground defects, or lumped components. Two different simulators, CST Electromagnetic EM simulator [10], and ADS circuit simulator [11] are used to simulate the proposed BLC. The proposed structure is fabricated and experimentally tested using vector network analyzer. A comparison between measured and simulated results has been made and very good agreement have been obtained. A comparative study between this proposed design and previously published related work have been presented [12 - 17]. In [12], Hybrid BLC was fabricated to operate at 1 GHz using six different capacitors. In [13], asymmetric T-structures were used to design BLC at 0.9 GHz with complex calculation to get the design parameters. In [14] CRLH-TL with meander shaped slots were used to design BLC at 0.7 GHz, where top and bottom layers for the ground defect were used. In [15] symmetrical and non-symmetrical T-shaped structures were used for designing the BLC to work at 2.4 GHz using qusi-lumbed elements a broach, with more than fifteen design parameters. In [16] discontinuous microstrip lines were used to design BLC at 1 GHz with unknown design parameters. In [17] Artificial transmission lines were used to design BLC at 1.8 GHz with large size compared to the other designs.

The paper is organized as follows: Section II, introduces the coupled line D-CRLH unit cell. Section III, shows the proposed compact BLC. Section IV, includes the comparison between the measured and simulated results, followed by the conclusion and references.

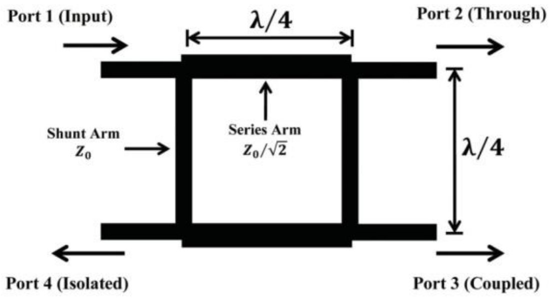


Fig. 1. Conventional branch-line coupler.

2. Coupled line D-CRLH unit cell

The conventional Composite Right/Left-Handed transmission line (C-CRLH-TL) unit cell was extensively presented in [18], as shown in Fig. 2(a). It consists of a series LC tank and shunt parallel LC tank circuits. Figure 2(b), shows D-CRLH TL [19], that consists of a parallel LC tank and shunt series LC tank circuits. The main difference between the two unit cells is the arrangement of the left and right hand frequency bands. In the first type (i.e., C-CRLH) the Left Hand (LH) band comes at low frequencies, while the Right Hand (RH) band comes at high ones. But, in the second type (i.e., D-CRLH) reverse situation is obtained. The D-CRLH, and C-CRLH unit cells may be combined together into an extended CRLH structure with intrinsic quad-band property [19], There are many structures that were designed to work as D-CRLH unit cells [6], [19].

In this paper, a very simple coupled line unit cell is used, it has a behavior same as D-CRLH, which was firstly presented in [8], and used in many applications [9, 20, and 21]. Fig. 3, shows the coupled line unit cell designed in three different shapes conventional coupled line, crescent shape, and fork shape. Each shape is suitable according to its characteristics and the design geometry requirements.

Two main parameters are used to characterize the CRLH TL, The dispersion relation β, and Bloch impedance ZB. The dispersion relation diagram is the relationship between the propagation constant β (m^{-1}) and the operating frequency. The Bloch impedance is defined as the characteristic impedance of the waves on the structure. Both parameters can be calculated as follows:

$$\beta = \frac{\cos^{-1} A}{p} \qquad (1)$$

$$Z_B = \frac{B}{\sqrt{A^2 - 1}} \qquad (2)$$

Where A, and B, are the first row of the (ABCD) matrix, (p) is the length of the unit cell. Equations (1) and (2) can be written as a function of the S-parameters [22].

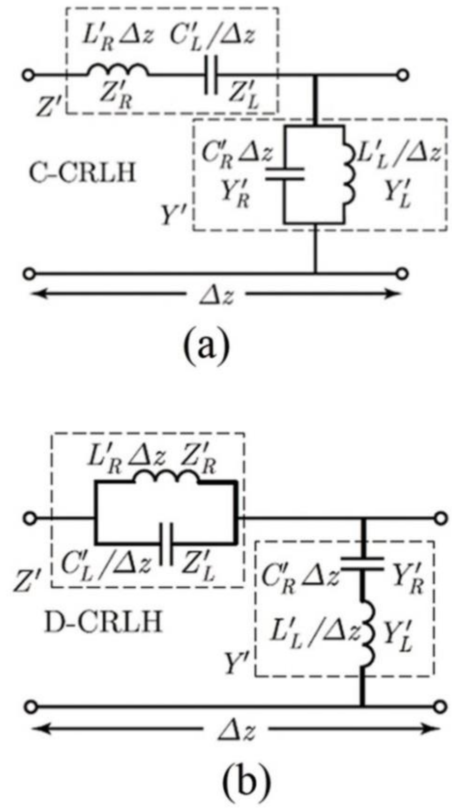


Fig. 2. Shows the equivalent circuit of the C-CRLH (a), and D-CRLH (b) [19].

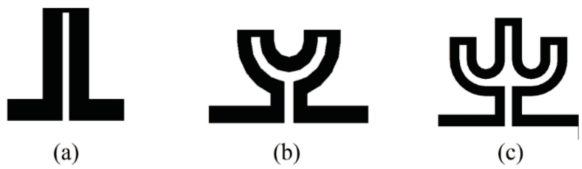


Fig. 3. Shows the three different structures of the coupled line D-CRLH (a) conventional coupled line, (b) crescent shape, and (c) fork shape.

$$\beta p = \frac{\cos^{-1}(1 - S_{11}S_{22} + S_{12}S_{21})}{2S_{21}} \qquad (3)$$

$$Z_B = \frac{2jZ_0S_{21}\sin(\beta p)}{(1-S_{11})(1-S_{22}) - S_{21}S_{12}} \qquad (4)$$

3. Design of branch-line coupler using coupled line D-CRLH unit cell

The proposed design is shown in Fig. 4 (b), it's composed of two different D-CRLH unit cells. The TL in the conventional BLC with impedance Z_0 = 50Ω was replaced by the D-CRLH crescent shape unit cell that is shown in Fig. 4 (a), while the TL of the conventional BLC with impedance Z_0 = 35Ω was replaced by the D-CRLH conventional coupled line unit cell which is shown in Fig. 4 (c). The relation between the width of the host TLs and the coupled TLs can be obtained by the following expression [1]:

$$Z_{Host\ TL} = \sqrt{Z_{odd} Z_{even}} \quad (5)$$

Where, $Z_{Host\ TL}$, Z_{odd}, and Z_{even} are the characteristic impedance of the host transmission line, odd and even mode characteristic impedances of the coupled line, respectively. To obtain matching condition between the host and coupled transmission line the ADS has been used to calculate the width of each TL. Table 1, shows the design specifications of the proposed BLC using coupled line D-CRLH unit cell.

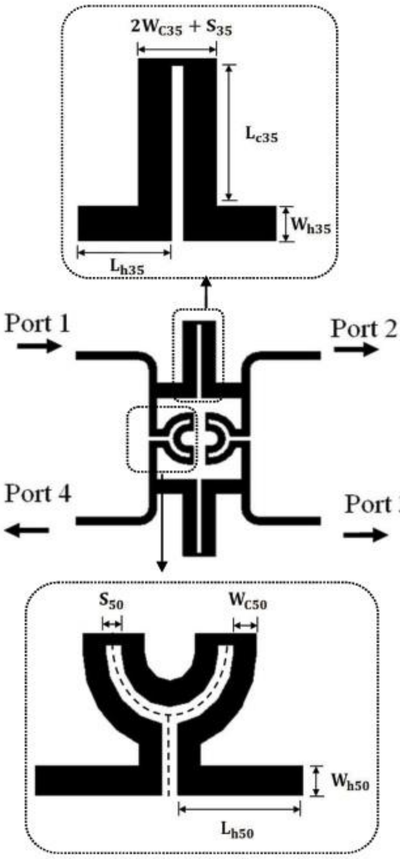


Fig. 4. (a) An enlarged image of the crescent shape unit cell, in case of Zo = 50Ω. (b) Proposed design of the compact BLC. (c) An enlarged image of the conventional coupled line unit cell, in case of Zo = 35Ω.

The dispersion relation diagram that is plotted in Fig. 5(a), shows the behavior of the crescent shape D-CRLH unit cell. The phase constant (in Radian) which is represented by the imaginary part of the propagation constant takes positive values in the first Right Hand (RH) band from 1 to 3.4 GHz, then the wave changes its behavior from Right Hand (RH) to the Left Hand (LH) band, then β becomes negative. In the LH band β increases with frequency until it reaches zero at 6.5 GHz, in which the frequency is known as balance frequency [18].

Table 1. Design specifications of the coupled line D-CRLH BLC.

	Z_o=35Ω	Z_o=50Ω
Host TL length	L_{h35}=4mm	L_{h50}=4mm
Host TL width	W_{h35}=1.54mm	W_{h50}=0.8mm
Coupled line	L_{c35}=6.2mm	Dash line=6.2mm
Coupled line width	W_{c35}=1.4mm	W_{c50}=0.7mm
Coupled line space	S_{35}=0.5mm	S_{50}=0.5mm

Since the unit cell has a good balance there is no stop band in the dispersion diagram [8]. The characteristic impedance of the coupled line D-CRLH unit cell is depicted in Fig. 5(b). It is clear that the unit cell has a good impedance match in the first RH band, which is about Z_0 = 50Ω. Hence, the proposed BLC is designed to work in the first RH band from 1 to 3.4 GHz, centered at 1.8 GHz.

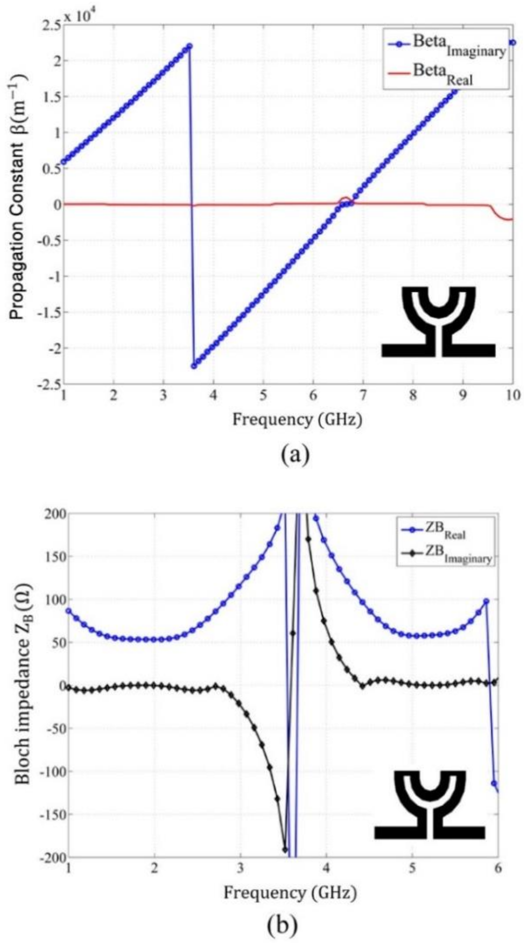
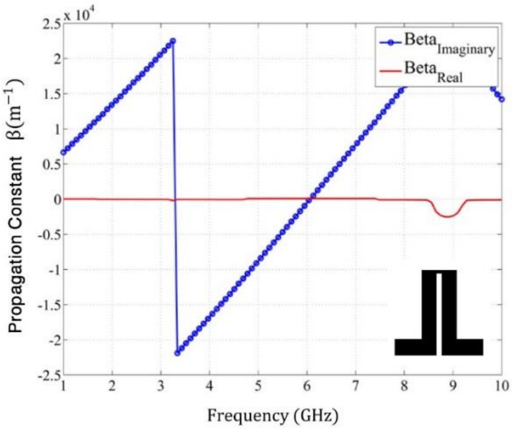
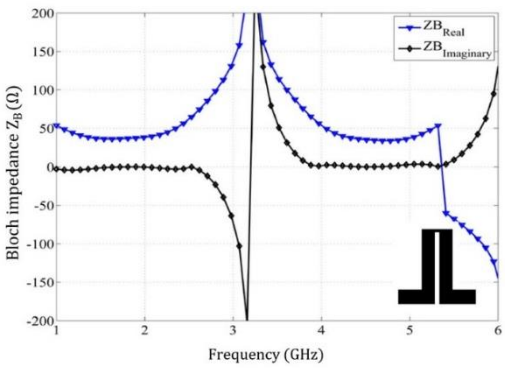


Fig. 5. Dispersion diagram β (m^{-1}) of the D-CRLH crescent shape unit cell (a), and Bloch impedance ZB (Ω), when Zo = 50Ω.

Similarly, the dispersion diagram and Bloch impedance of the D-CRLH conventional coupled unit cell was plotted in Fig. 6. The main different is the value of the characteristic impedance which Zo=35Ω for this unit cell.



(a)



(b)

Fig. 6. Dispersion diagram β (m^{-1}) of the D-CRLH conventional coupled line unit cell (a), and Bloch impedance ZB (Ω), when Zo = 35Ω.

4. Comparison between the measured and the simulated results

The compact BLC was implemented on dielectric substrate ε_r= 6.15, and thickness h= 0.358 mm. Fig. 7, shows the photograph of the fabricated compact BLC. The fabricated design is tested using vector network analyzer (HP8719ES). A comparison between the measured results and both simulators' results is shown in Fig. 8 (a) for the magnitudes of the (S_{11} and S_{12}), and (b) for the magnitudes of the (S_{13} and S_{14}). Very good agreement has been obtained. The measured return loss S_{11} is about -15dB from 1.6 to 1.95 GHz, with a 18.9% relative bandwidth. The isolation S_{14} is also better than -15dB from 1.6 to 1.95 GHz. The output power is split equally between ports 2 and 3 with magnitude (-3 ± 0.1) dB in the frequency band extends from 1.6 to 1.95 GHz.

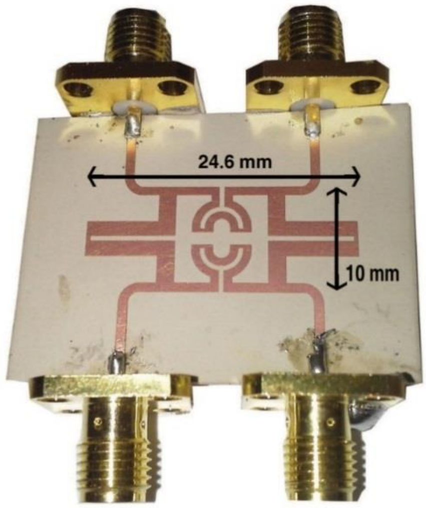
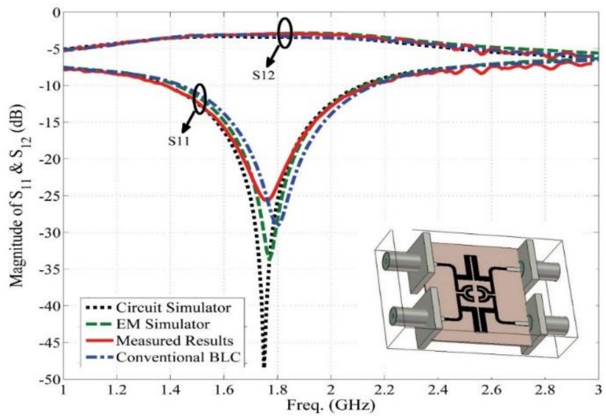
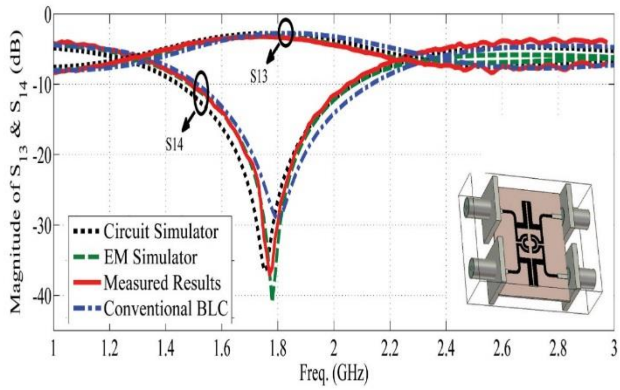


Fig. 7. The photograph of the fabricated BLC using D-CRLH coupled line unit cells.



(a)



(b)

Fig. 8. Comparison between measured results, circuit simulator, EM simulator, and conventional BLC, (a) for the (S_{11} and S_{12}), and (b) for the (S_{13} and S_{14}) magnitudes.

The phase difference between S_{12}, and S_{13} is plotted in Fig. 9 .It is shown that, neglecting the effect of the SMA coaxial modeling, the S_{13} phase difference is in between ($90^{\circ} \pm 5^{\circ}$), while the S_{12} is in between ($180^{\circ} \pm 5^{\circ}$). But when the SMA effect is taken into account, the phase differences change dramatically, S_{13} phase becomes in between ($20^{\circ} \pm 5^{\circ}$), and S_{12}, is in between ($100^{\circ} \pm (5^{\circ})$, that means SMA coaxial connectors have a clear effect on the phase difference change.

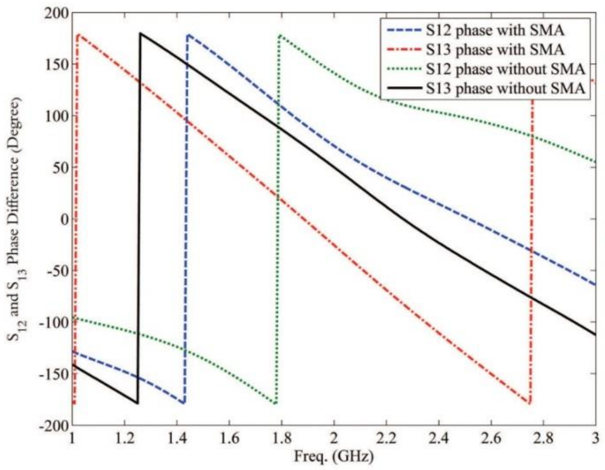


Fig. 9. Shows (S_{12} and S_{13}) phase difference, with and without SMA modeling effects.

The introduced BLC has over all area of $10 \times 24.6 = 246\ mm^2$. Since, the conventional branch-line coupler area are 21.39×22.11= 472.9 mm^2 at 1.8 GHz, the proposed BLC occupies only 52% area of the conventional design, without degradation in its performance, The proposed design has a high competitive performance compared to the previously published work as shown in Table 2.

There are many advantages make the proposed BLC more competitive than others. The simplicity in the design and fabrication comes at the top of these features. ADS can be used effectively to get the design parameters. Moreover, a very simple PCB fabrication technique can be used to realize the design without lumped elements or ground defect. The proposed BLC is designed to operate at 1.8 GHz, but can be re-designed easily to work at any specific frequency. As shown in table 2, the proposed BLC have the efficient return loss ($S_{11} = -35$ dB), and good isolation ($S_{14} = -25$ dB). The percent bandwidth is about 18.9% at $S_{11} = -15$ dB, which can be enhanced by adding another BLC box but the size of the design will be increased. Another advantage, is the splitting of the power equally at the two output ports (through and coupled) over a wide range of frequencies from 1.56 to 2 GHz with magnitude imbalance (3 ± 0.1 dB). The effective design area of the proposed coupler is $246\ mm^2$, which is dependent mainly on the operating frequency (i.e., 1.8 GHz). As shown in Table 2, the design in [17] works at the same frequency and occupies $687\ mm^2$ which is more than double of the proposed design area.

Table 2. Comparison between the performance of the previous published work and the proposed BLC.

	Reff.[12]	Reff.[13]	Reff.[14]	Reff.[15]	Reff.[16]	Reff.[17]	EM Simulated Conventional BLC	The proposed BLC
Frequency work f_o GHz	1	0.9	0.7	2.4	1	1.8	1.8	1.8
Insertion Loss S_{11} dB @ f_o GHz	-16.9	-29	-23	-28	-35	-30	-29	-35
Isolation S_{14} dB @ f_o GHz	-25.3	-22	-22	-24	-35	-30	-29.15	-25
Coupling S_{13} dB @ f_o GHz	-3.5	-3.25	-3.3	-3.4	-2.5	-3	-3.3	-3
Bandwidth @ S_{11} = -15 dB	10%	17%	2%	10%	20%	16.7%	18.8%	18.9%
Circuit area mm^2	388	333.7	1267.2	109.8	170	687	472.9	246
Relative size	12.7%	12.2%	22.8%	29%	41%	48%	100%	52%
Fabrication technique	PCB, and lumped components	PCB	PCB and defect ground	PCB, high-impedance TL.	PCB, high-impedance TL.	PCB	-	PCB

5. Conclusion

A very simple coupled line (D-CRLH) unit cell was used to design a new compact BLC. The dispersion relation and Bloch impedance for the unit cell was plotted and show good impedance matching in wide range of frequencies. The proposed BLC is designed to work in the RH region to get full matching. PCB technique without lumped components, via holes, or ground defects was used to fabricate the D-CRLH BLC that occupies only 52% area of the conventional one without any performance degradation. A comparison between the measured and the simulated results using both CST and ADS simulators shows very good agreement.

A comparative study between the proposed BLC and another six different BLCs published previously has been presented. The comparison shows how the proposed BLC overcome the drawbacks of the other BLCs with efficient performance.

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