Using a VIA-Less CRLH Transmission Line to Design a Compact Wilkinson Power Divider and Rat-Race Coupler

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***Abstract*─** A method for design and implementation of a compact via-less CRLH transmission line is presented. By introducing a new circuit model, the CRLH transmission line behavior is explored versus the parameters variations to achieve the desired characteristic impedance and electrical length. Then a compact quarter wavelength CRLH transmission line with 70 Ω characteristic impedance is designed as an example. Finally a very compact four way Wilkinson power divider and a rat-race coupler are designed and fabricated by using this type of CRLH TL which have about 75% and 80% compactness, respectively.

***Index Terms*─** CRLH, Transmission line, Wilkinson divider, Rat Race, Coupler

I. INTRODUCTION

From the introducing of the backward wave propagation supporting materials which have opposite sign in the phase and group velocities, the different realizations approach of these materials has been reported such as wire medium [1-3], multilayer structure [4], and photonic crystal [5]. The left handed (LH) structure is another ways for implementing of these artificial media [6-16]. The LH transmission line consists of transmission line unit cells loaded by series capacitance and shunt inductance which lead to new microwave applications based on its unique backward wave characteristics [17-18]. Due to the intrinsic parasitic series inductance and shunt capacitance in the transmission line structure, it is impossible to have a pure LH transmission line. Therefore, by modeling these parasitic elements one can achieve a complete transmission line model called composite right/left-handed transmission line (CRLH TL) which has been introduced in [19]. The CRLH TL behaves as a LH at low frequencies, while at high frequencies it acts as a conventional transmission line. Direct implementation of the CRLH TL structure imposes using a short circuit stub which is grounded by a via connection. But, the via fabrication process is not as easy as a planar fabrication. Furthermore, it causes some undesirable effects on the designed prototype such as radiation [20] and the frequency shift [21] especially at higher frequencies. To overcome these issues, the coplanar waveguide configuration has been used in [22]. Since the ground conductors and signal line are in the same plane in this type of CRLH TL, the shunt inductances can be accommodate without having vias.

In our previous work [28], a new via free microstrip CRLH TL is considered to achieve a low cost and easy fabrication microwave devices. This new CRLH TL which is based on the unit cell introduced in [23] is modeled by a new circuit model which is more matched with the structure behavior. Moreover, compare with [23], in this paper the effects of the CRLH TL parameters in the electrical length and characteristic impedance of the unit cell are analyzed and simulated to extend the application of the introduced CRLH TL in microwave devices. This work can be an extension over previous works such as [29-32] that tries to compact the TLs in microwave devices.

[DOI: 10.22068/IJEEE.11.1.1]

The results show that this CRLH transmission line can achieve a wide range of electrical length and characteristic impedance with shorter physical length. Therefore, this CRLH TL can be used for miniaturization of the microwave devices. After it, a CRLH TL is optimized to design a quarter wavelength transmission line with 70 Ω characteristic impedance as an example. Finally, the CRLH TL is used instead of the ordinary transmission line in a four way Wilkinson power divider and a rat-race coupler. The simulation and measurement results of these devices show about 75% and 80% compactness compared with the traditional ones which verify the high capability of the method in compacting the microwave devices.

II. CRLH Transmission Line Modeling

A common CRLH TL unit cell is composed of a series capacitance, shunt inductance, series inductance and shunt capacitance [6]. The CRLH unit cell configuration and its schematic are shown in Fig.1. This model describes the structure behavior much better than [23] presented circuit model. The main difference is the capacitance due to the gap between the meander line segments that causes a series resonance in vertical branch is modeled in Fig.1. The model is composed of series capacitor (C_{HS}) which is a metal-insulator-metal (MIM) capacitor, a vertical capacitor (C_{VS}) achieved by the effect of the gap between two MIM capacitors, the parallel combination of vertical inductor (L_{VP}) and vertical capacitance (C_{VP}) resulted from the meander inductor located at the PCB ground, and the series inductor (L_{HS}) belongs to the defected ground structure (DGS) effective inductance. In order to change the circuit elements, some parameters are defined to change the element values. The S_{cap} and w_{cap} are defined to tune the gap and MIM capacitors. Also, as shown in Fig.1.a, the length, width and the space between the meander line segments are defined by l_{cap}, w_{mndr} and S_{mndr}, respectively which change the C_{VP} and L_{VP}. Moreover, the l_{HS} affects the L_{HS} value.

Notice that the defected ground structures (DGS) are usually modeled with a parallel conductance, capacitance and inductance [24], but here we are far from the DGS resonance frequency and therefore we can ignore the effect of conductance and capacitance of the DGS inductance. This effective inductance can be tuned by changing the top microstrip transmission line width and the width of etched part in the ground defined by S_x. Also, due to the specific required width of the microstrip transmission line to achieve 50 Ω input impedance, the effective inductance of DGS can be controlled by S_x.

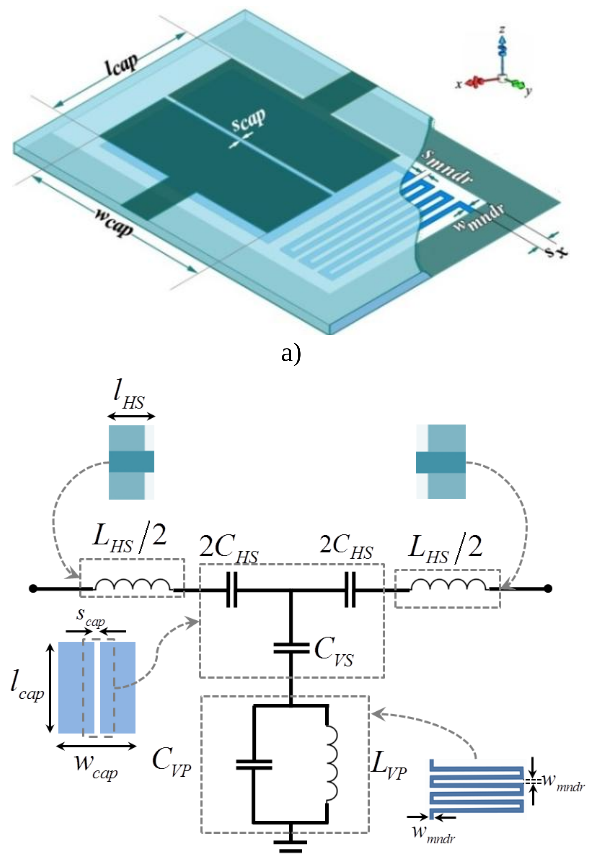


Fig. 1. Proposed composite right/left-handed transmission line a) 3D structure b) circuit model

The characteristic impedance (Z_C) for this CRLH TL structure can be calculated by using familiar procedure mentioned in [25], which is

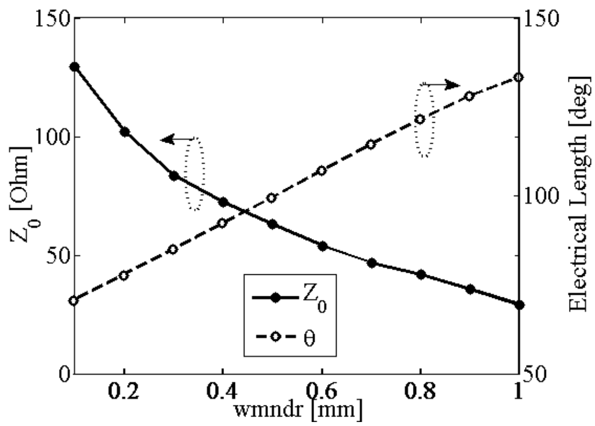
$$Z_C = \sqrt{\frac{Z}{Y}} = Z_L \sqrt{\frac{((\omega/\omega_H)^2 - 1)((\omega/\omega_{V1})^2 - 1)}{(\omega/\omega_{V2})^2((\omega/\omega_{ind})^2 - 1)}} \qquad (1)$$

where $\omega_H = \sqrt{1/C_{HS}L_{HS}}$, $\omega_{V1} = \sqrt{1/((C_{VP}+C_{VS})L_{VP})}$, $\omega_{V2} = \sqrt{1/(C_{VS}L_{VP})}$, and $\omega_{ind} = \sqrt{1/(C_{VP}L_{VP})}$ are the horizontal branch, first and second vertical branch, and meander inductor resonance frequencies, respectively. Moreover, $Z_L = \sqrt{L_{VP}/C_{HS}}$ is the left handed impedance of the CRLH TL unit cell. This relation shows that the CRLH characteristic impedance is generally depended on the frequency. To design this CRLH TL, a parameter called scale is assigned in the model to scale all the unit cell physical parameters such as l_{cap}, w_{cap}, S_x, w_{mndr} and S_{mndr}, identically and changing the operation frequency, consequently. The simulation results show that the CRLH TL characteristic impedance can be decreased by increasing w_{mndr} and S_{mndr}, while the electrical length is increased, accordingly. Also, the total inductance of meander inductor is increased when the distance between meander line turns and width are increased [26] and therefore, we can see that the coupling between meanders (C_{VP}) increases which decreases the second resonance frequency of vertical branch (ω_{V2}) and decrease Z_C, consequently. On the other hand, since the capacitance of a parallel plate capacitor, C_{HS}, is growth by increasing of the plates area, enhancement of w_{cap} and l_{cap} increase the characteristic impedance and decrease the electrical length and the horizontal branch resonance frequency (ω_H). To extract the equivalent characteristic impedance and electrical length of the designed CRLH TL from the S-parameters of the simulation results, the below relation can be used [27]

$$Z_c = Z_0\sqrt{\frac{(1+S_{11})^2 - S_{21}^2}{(1-S_{11})^2 - S_{21}^2}} \tag{2}$$

where Z_C and Z_0 are the CRLH TL and reference characteristic impedance, respectively. Also, the electrical length is equal to the argument of S_{12}. The commercial full wave simulator software (Ansoft HFSS) has been used to simulate the CRLH TL unit cell. Figure 2 shows the effect of w_{mndr} and w_{cap}, separately. The effect of l_{cap} in electrical length is similar with w_{cap} except l_{cap} has a more effect on characteristic impedance. In addition, the place of the two 50 Ω lines in the both sides of CRLH TL has negligible effect on both characteristic impedance and electrical length. Now we are ready to design a CRLH TL to achieve a 70.7 Ω characteristic impedance and 90 degrees electrical length which can be used to design some well known microwave devices such as Wilkinson power divider and rat-race coupler.

Based on the effect of each parameter which was discussed and studied in the design producer, the CRLH TL can be tuned to achieve the desirable specifications. The designed CRLH TL has the real characteristic impedance of 72.2Ω, small imaginary part of 0.2 Ω and an electrical length of 90 degrees at the design frequency, 460 MHz. The TLX-8 substrate with a dielectric constant of 2.55, a tangent loss of 0.0019 and a thickness of 0.8 mm has been selected as the substrate of the CRLH TL. The values of the circuit and physical parameters are tabulated in Table I.



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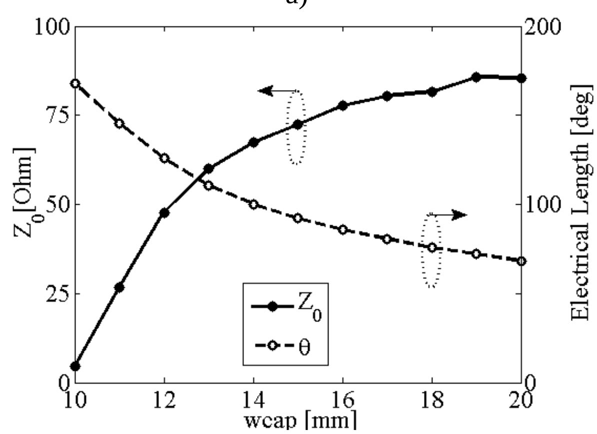

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Fig. 2. Characteristic impedance and electrical length variations as a function of w_{mndr} and w_{cap}

TABLE 1 :Circuit and Physical Parameters Value

Circuit elements	Physical Parameters	Value	Description
L_{VP} = 6.97 nH C_{VP} = 0.21 pF	w_{mndr} S_{mndr}	0.45mm 0.4 mm	meander inductor
L_{HS} = 7.62 nH	s_x	1 mm	DGS inductance
C_{HS} = 2.75 pF	w_{cap} l_{cap}	16.5 mm 12 mm	series capacitance
C_{VS} = 0.2 pF	s_{cap}	0.2 mm	gap effect

III. Wilkinson Implementation

Based on the designed CRLH TL in the previous section, a miniaturized four way Wilkinson power divider is designed and fabricated on the TLX-8 substrate at 460 MHz which is shown in Fig. 3. The designed four ways Wilkinson power divider is composed of three identical two ways Wilkinson power dividers. The 70.7 Ω ordinary quarter wavelength microstrip lines in the conventional Wilkinson power divider are replaced by designed CRLH TL in the previous section which has 72.2 Ω characteristic impedance and 90 degree electrical length.

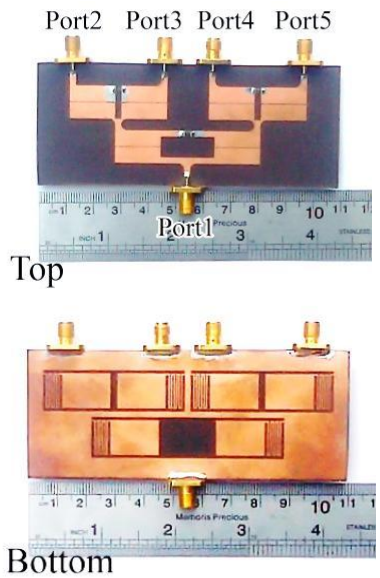
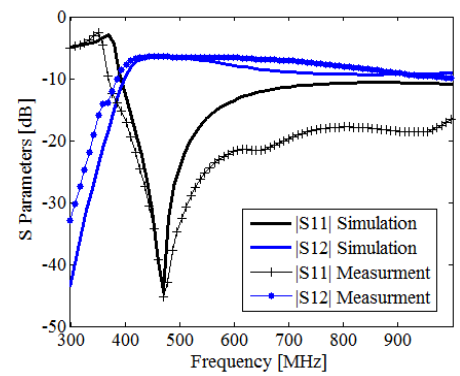


Fig. 3.Top and bottom view of 1 to 4 Wilkinson power divider

Although the designed CRLH in the previous section was simulated completely, but to consider the coupling effect of the CRLH TL segments in the four way Wilkinson dividers, the full wave simulation of the power divider is done. Figure 4 shows the comparison of the full wave simulation and measurement results of the designed CRLH TL power divider. The electrical performance of the power divider is measured by using Agilent E5071C network analyzer. The simulated and measured return losses, insertion losses and isolations are shown in this figure. The plots represent a good agreement between simulation and measurement results. The power divider has a return loss better than 30 dB and an insertion loss less than 6.4 dB for all ports. Also, the isolation is more than 15dB for adjacent ports (2-3 and 4-5) and more than 25dB for non-adjacent ports (2-4 and 3-5). The designed CRLH Wilkinson power divider has about 75% area reduction compared with the traditional one at the design frequency.

IV. Rat Race Implementation

In this section, the designed CRLH TL is used to miniaturize another microwave component, rat-race coupler. The conventional rat-race coupler consists of three identical uniform transmission lines with a characteristic impedance of 70.7 Ω and 90 degree electrical length and another transmission line with the same characteristic impedance but 270 degree electrical length. Therefore, this device can be considered as a six quarter wavelength uniform transmission lines which occupy huge circuit area. For miniaturizing of this component, the uniform conventional transmission lines are replaced by the designed CRLH TL in Sec. II.



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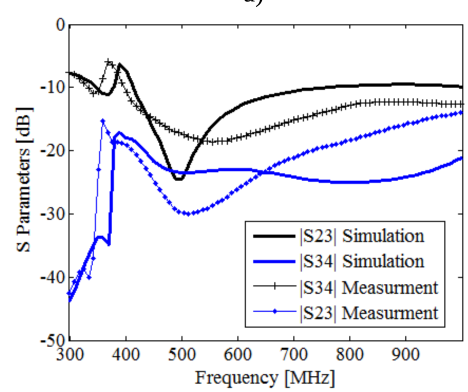

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Fig. 4.The S parameters comparison of the simulation and measurement results four ways Wilkinson power divider a) $|S_{11}|$ & $|S_{12}|$ and b) $|S_{23}|$ & $|S_{34}|$

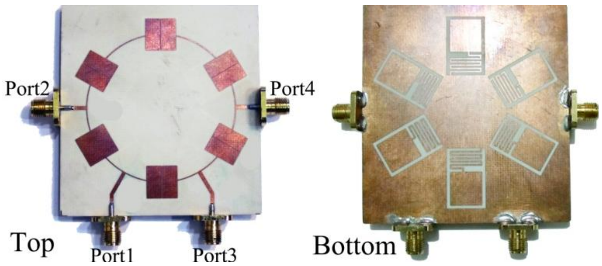
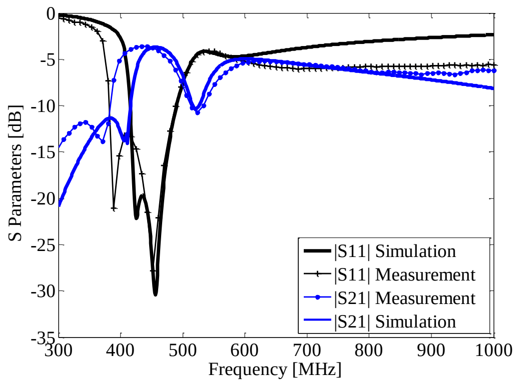


Fig. 5.Top-view and bottom-view of Rat Race



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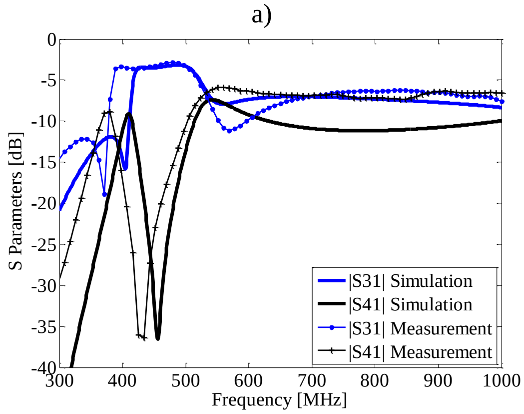

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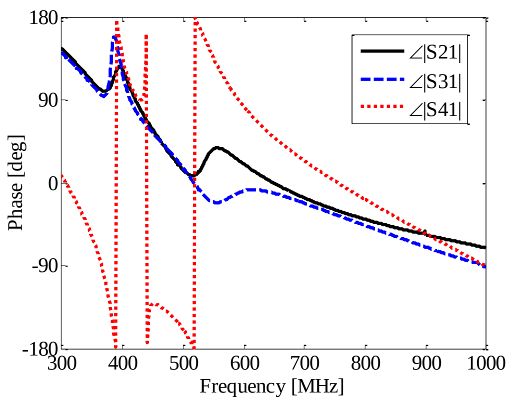

c)

Fig. 6.The S parameters comparison of the simulation and measurement results of Rat Race a) $|S_{11}|$ & $|S_{21}|$ and b) $|S_{31}|$ & $|S_{41}|$

The designed CRLH TL rat-race coupler is shown in Fig.5 which is fabricated on the TLX-8. It can be seen that the useless interior space of the designed rat race is filled by the CRLH TLs. Same as the design approach for the Wilkinson divider in the previous section, the rat-race coupler composed of CRLH TL segments is simulated by HFSS, completely. The simulation and measurement results of the coupler are compared in Fig. 6. There is a small frequency shift and a reduction in bandwidth which may be caused by commercial fabrication processes.

Table2: Comparison between proposed structures and references

References	Compactness	Limitation
Introduced in [11]	50 %	
Introduced in [12]	91%	Using Lumped Elements
Introduced in [13]	85 %	Hybrid of Slow Wave and CRLH TL
Introduced in [14]	77%	Using Lumped Element
Introduced in [15]	93%	Using Multilayer structure
This paper	**80%**	

The designed device has a return loss less than 30 dB, an insertion loss less than 3.2 dB. Also, the isolation between port 1 and 4 is better than 35dB. The Comparison between the conventional and designed rat-race shows that using the designed CRLH TL unit cells instead of the conventional uniform transmission lines, an area size reduction more than 80% can be achieved at the design frequency, 460 MHz.

In Table 2, our proposed structures are compared to some other metamaterials Wilkinson and rat-race power dividers obtainable in the literature. It can be seen that the proposed structures have a very compact dimension compared to the others.

V. Conclusion

An improved method to design a via-less CRLH TL was developed and a new circuit model of this TL has been presented. Moreover, the effects of the CRLH TL design parameters were discussed. Then, a CRLH TL with a real characteristic impedance of 72.2 Ω and electrical length of 90 degrees was designed as an example which is used in implementation of a high compact four way Wilkinson power divider and rat-race coupler. The designed power divider and rat-race coupler by CRLH TL unit cells shown about 75% and 80% compactness compared with the conventional ones.

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