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# Modified Extended Composite Right/Left-Handed Layout Loaded with CSRR for Quad Band Applications

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**Abstract**—This paper presents the design and implementation of a novel fully planar modified, extended composite right/left-handed transmission lines (E-CRLH-TLs) utilizing a complementary split ring resonator (CSRR) loaded on the ground plane. The multiband behavior of the proposed layout is demonstrated by an equivalent circuit which in this case is distinct from the standard form of the equivalent circuits presented for an E-CTLH-TL; therefore, in order to design a quad band E-CRLH unit-cell, the design procedure is investigated. The main advantages of the proposed layout over other topologies are size reduction and fabrication simplicity which are proved by the design and fabrication of a quad-band Y power divider.

## 1. INTRODUCTION

As most of the networks are changing to operate at more than one frequency band, dual and multiband microwave components are required for implementation of such networks. Composite right/left-handed transmission lines (CRLH-TLs) introduced by Caloz et al. [1] recommended an attractive method for developing dual-band components since they have one right- and one left-handed propagation bands. Using this kind of transmission lines, numerous dual-band structures have been deigned in [2–7]. The Extended CRLH-TLs presented in [8, 9] are a generalized form of the CRLH-TLs proposed by combining conventional CRLH (C-CRLH) and dual CRLH transmission line introduced in [10]. E-CRLH-TLs have two more right/left-handed frequency bands due to owning two more resonators, and by engineering the impedance and dispersion characteristics, they can be utilized in developing dual- and quad-band devices as reported in [11–20].

Having two extra resonators in E-CRLH-TLs which add up four more reactive elements to equivalent circuit and equations, complicates the design and implementation procedure. Up to now, various layouts and design procedures have been proposed for implementing an E-CRLH structure. In [11], a quad-band Wilkinson power divider is fabricated in microstrip technology utilizing chip capacitors and inductors; however, in [18, 19, 21] quad-band Y power splitters and branch line coupler are implemented in a fully planar configuration using microstrip and SIW technology.

In this paper, a novel fully planar layout is proposed for the implementation of E-CRLH-TLs, and it is intended to reduce the size of the structure with the CSRR loaded on ground plane which operates as one of the four resonators of E-CRLH transmission lines. The equivalent circuit model of the presented layout is depicted in Fig. 1(c). This model is distinct from the conventional equivalent circuit of E-CRLH-TLs, but it exhibits alternated four right/left-handed bands. The feature is demonstrated by designing a quad-band impedance inverter which is utilized in developing a quad-band power splitter.

The paper is organized as follows. In Section 2, the topology and the modified equivalent circuit are demonstrated, and the design procedure is described. Section 3 presents the design and simulation of a quad-band impedance inverter. In Section 4, the quad-band impedance inverter is used to develop

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a quad-band power splitter, and the results are compared to previous works. Finally in Section 5, the paper ends with conclusions.

## 2. THE THEORY AND DESIGN PROCEDURE

The proposed layout and its lossless equivalent circuit designed to behave as a quad band impedance inverter is depicted in Fig. 1. $L_{hp}$ and $C_{hp}$ are realized by an interdigital capacitor with a narrow strip line parallel with it. $L_{hs}$ and $C_{hs}$ are implemented by meander inducer and interdigital capacitor. $L_{vp}$ and $C_{vp}$ are achieved by a stub connected to the ground by vias, and the CSRR etched on the ground plane realizes $C$, $C_c$ and $L_c$.

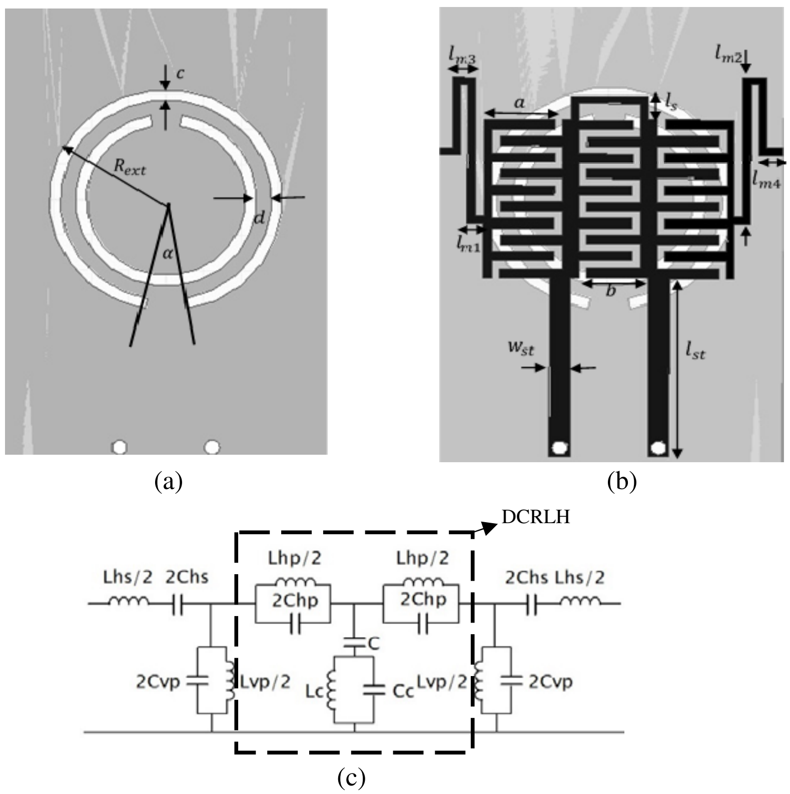



**Figure 1.** The proposed topology for a modified E-CRLH-TL, (a) top view, (b) bottom view, (c) equivalent circuit. The unitcell dimensions are: $a = 1.75\,\text{mm}$, $b = 1.57\,\text{mm}$, $c = 0.3\,\text{mm}$, $d = 0.4\,\text{mm}$, $w_s = 0.2\,\text{mm}$, $l_s = 0.49\,\text{mm}$, $R_{ext} = 3.13\,\text{mm}$, $w_{st} = 0.52\,\text{mm}$, $l_{st} = 5\,\text{mm}$, $l_{m1} = 0.41\,\text{mm}$, $l_{m2} = 3.9\,\text{mm}$, $l_{m3} = 0.6\,\text{mm}$, $l_{m4} = 0.61\,\text{mm}$ and $D = 0.5\,\text{mm}$. The width of digits in central and two other capacitors are 0.26 mm and 0.265 mm respectively. The line width of meander line and all spacing in interdigital capacitor are 0.2 mm.

The first step in the design of a quad-band transmission line is to find the values of the lumped elements in the equivalent circuit. For this purpose, the propagation constant and characteristic impedance of the transmission line can be easily obtained by applying a periodic analysis, from which we have

$$\beta d = \cos^{-1}(A) \tag{1}$$

$$Z_B = \frac{\pm B}{\sqrt{A^2 - 1}} \tag{2}$$

where $A$ and $B$ are the elements of $ABCD$ transmission matrix, and $\pm$ signs show that $Z_B$ has plus and minus sign respectively in LH and RH frequency bands. As it is known in order to determine the design equations, first of all the elements of the matrix should be obtained by multiplication of $ABCD$ matrices of each part in equivalent unit cell, respectively, as given in

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & Z_{hs} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Y_{vp} & 1 \end{bmatrix} \begin{bmatrix} 1 & Z_{hp} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Y_{vs} & 1 \end{bmatrix} \begin{bmatrix} 1 & Z_{hp} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ Y_{vp} & 1 \end{bmatrix} \begin{bmatrix} 1 & Z_{hs} \\ 0 & 1 \end{bmatrix} \tag{3}$$

Here $Z_{hs}$, $Y_{vp}$, $Z_{hp}$ and $Y$ are

$$\begin{aligned} Z_{hs} &= \frac{1}{j2\omega C_{hs}} + j\omega L_{hs}/2 \\ Y_{vp} &= \frac{2}{j\omega L_{vp}} + j\omega 2C_{vp} \\ Z_{hp} &= \left(\frac{2}{j\omega L_{hp}} + j\omega 2C_{hp}\right)^{-1} \\ Y_c &= \left(\frac{1}{j\omega C} + \frac{j\omega L_c}{1-\omega^2 L_c C_c}\right)^{-1} \end{aligned} \tag{4}$$

By defining $X$, $Y$ and $Z$ as:

$$\begin{aligned} X &= 1 + Z_{hs}Y_{vp} \\ Y &= 1 + Z_{hp}Y_{vs} \\ Z &= Z_{hp}(1 + Z_{hp}Y_{vs}) + Z_{hp} \end{aligned} \tag{5}$$

$A$ and $B$ elements of the matrix are obtained as

$$\begin{aligned} A &= XY + Z_{hs}Y_{vs} + Y_{vp}XZ + Z_{hs}YY_{vp} \\ B &= Z_{hs}XY + Z_{hs}^2Y_{vs} + X^2Z + XZ_{hs}Y \end{aligned} \tag{6}$$

Now to design a quad-band impedance inverter we have to set $\beta d$ equal to 90 degree and $Z_B$ equal to impedance of line at four arbitrary design frequencies, which leads to eight nonlinear equations with nine unknowns as

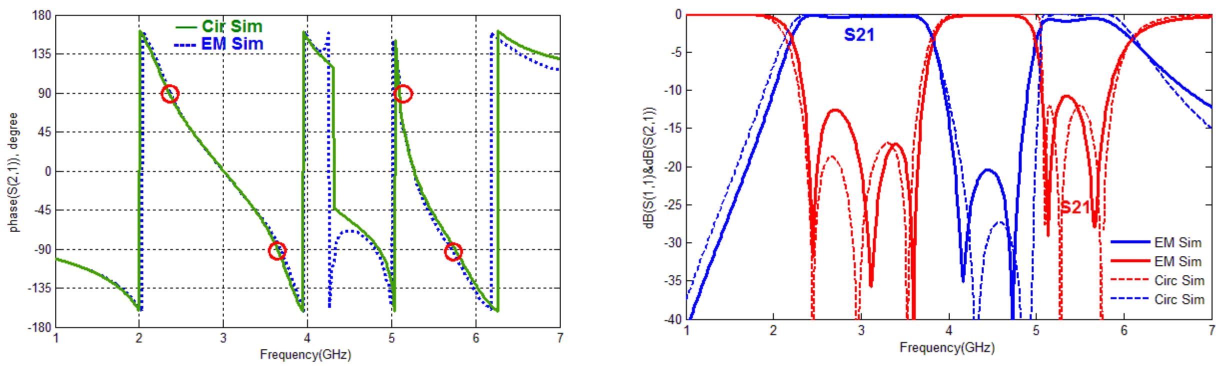
$$\begin{aligned} \pi/2 &= \cos^{-1}(A_i) \\ Z_B &= \frac{\pm B_i}{\sqrt{A_i^2 - 1}} \qquad (i = 1, 2, 3, 4) \end{aligned} \tag{7}$$

These equations can be easily solved using genetic optimization algorithm in Matlab, and the elements' values can be determined clearly.

After finding the elements' values for the desired design, the next step is to calculate the first tentative layout dimensions by means of parameter extraction. To do this, each part is simulated separately, and their parameters are extracted using the method presented in [22] for CSRR and the procedure demonstrated in [23] for other parts. The last step is to do an optimization in order to take into considerations the parasitic effects and find the final dimensions.

## 3. A QUAD BAND IMPEDANCE INVERTER

In this section, the procedure is applied to the design of a quad-band impedance inverter by means of one cell of the E-CRLH transmission line. The characteristic impedance is set to $Z_B = 35.35\,\Omega$, and the four operative frequencies are chosen as $f_1$ =2.4 GHz, $f_2$ = 3.6 GHz, $f_3$ = 5.1 GHz and 5.7 GHz. The elements' values that meet the requirements obtained by solving the equations are: $L_{hs} = 6.039$ nH, $C_{hs} = 0.385$ pF, $L_{vp} = 4.347$ nH, $C_{vp} = 0.305$ pF, $L_{hp} = 0.949$ nH, $C_{hp} = 1.113$ pF, $L_c = 0.723$ nH, $C_c = 1.083$ pF and $C = 0.797$ pF. The final layout acquired by parameter extraction and subsequent optimization is depicted in Fig. 1. The structure is designed on a substrate of Rogers4003 with dielectric constant of 3.55 and thickness of $h = 1.524$ mm. The magnitude and phase response of simulated $S$ parameters inferred from full wave simulations (using HFSS) are indicated in Fig. 2. For comparison, the results of equivalent circuit simulations are also indicated. As obvious from the figure, there is a good agreement between circuit and full wave simulations. The phase of $S_{21}$ depicted in Fig. 2(a)



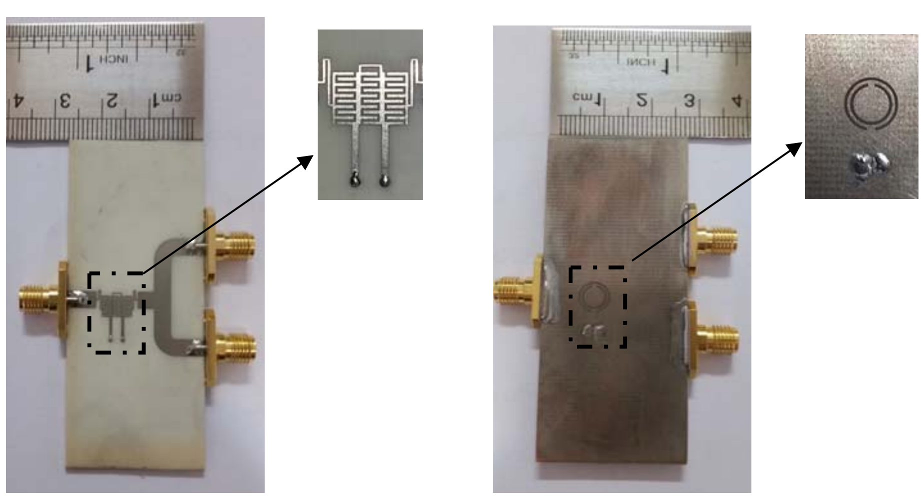

(a) (b)

**Figure 2.** Simulated frequency response of a quad band impedance inverter. (a) Phase of $S_{21}$, (b) magnitude of $S_{11}$ and $S_{21}$.

confirms that the required $\pm 90$ degree phase shift is obtained at each design frequency, and the E-CRLH cell behaves as a quad-band $\lambda/4$ transmission line. This can be utilized to realize the microwave devices such as couplers and dividers in which $\lambda/4$ transmission lines are the key components. The magnitude of $S_{11}$ shown in Fig. 2(b) is below $-12$ dB at four operative frequencies, which confirms good matching level.

## 4. QUAD-BAND POWER DIVIDER

To show the quad-band feature of the designed impedance inverter, in this section, a quad-band Y power divider is implemented simply by adding two $50\,\Omega$ transmission lines to the output ports and exciting the input port by an extra $50\,\Omega$ transmission line. Photographs of the fabricated device are shown in Fig. 3, and the $S$ parameter response of the power divider obtained from measurements is depicted in Fig. 4. For comparison, the results obtained from electromagnetic simulations are also included. There is good agreement between simulated and measured results, and the reason for the slight discrepancies is related to fabrication tolerance. It should be noted that the resonant feature of the structure makes frequency responses sensitive to geometric dimensions so that the acceptable tolerance for the final



(a) (b)

**Figure 3.** Fabricated CSRR loaded quad band power divider. (a) Top view. (b) Bottom view.

layout of the power divider is about 5 microns. The measured $S_{11}$, which represents the matching level, is better than 10 dB at four operative bands. The fractional bandwidths of 9%, 16.4%, 0.7% and 6.7% are achieved, respectively at first, second, third and fourth frequency bands. Moreover, the $S_{21}$ losses for the four bands are 4 dB, 3.9 dB, 4.9 dB and 4.9 dB, respectively.

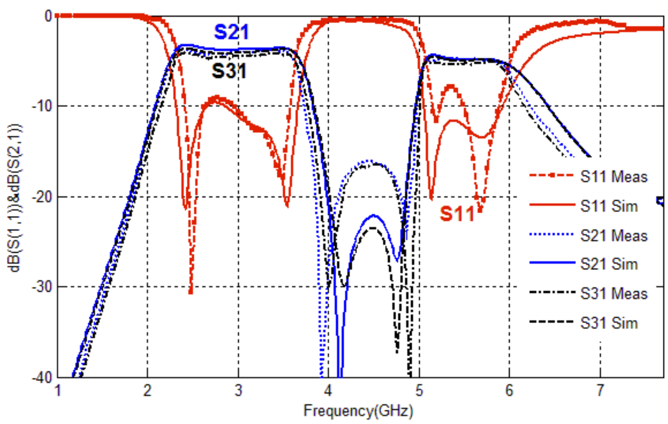



**Figure 4.** Simulated and measured $S$ parameters of a quad band Y power divider.

The size of the structure, excluding the access line, is 8.27 mm×7.33 mm which corresponds to $0.07\lambda_{01} \times 0.06\lambda_{01}$ and $\lambda_{g1}/8/5 \times \lambda_{g1}/9/85$ ($\lambda_{01}$ and $\lambda_{g1}$ are respectively the free space and guided wavelength at the lowest frequency band), and the advantage of the layout is due to implementing the DCRLH part of the equivalent circuit with a single $L_{hp}/C_{hp}$ resonator and CSRR resonator etched on the ground plane, which decreases the size and complexity of structure.

## 5. CONCLUSIONS

To decrease the size and complexity of an E-CRLH transmission line, a novel layout using a CSRR resonator loaded on the ground plane is introduced for the first time. The equivalent circuit which is different from the conventional form of an E-CRLH transmission line is derived for the proposed layout, and the procedure to design a quad-band impedance inverter is presented. To show the quad-band functionality of the proposed design a quad-band Y power divider is designed and fabricated, and there is a good agreement between simulated and measured results.

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