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SIMPLIFIED EXTENDED COMPOSITE RIGHT/LEFT-HANDED TRANSMISSION LINE STRUCTURE FOR DUAL-BAND APPLICATIONS

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Abstract—A simplified extended composite right/left-handed (SE-CRLH) transmission line (TL) is proposed for dual-band applications. The dual-band bandpass behavior is realized with a simplified non-dual circuit with only two broadband balanced conditions. The dispersion relation and frequency response of SE-CRLH TL are analyzed by circuit analysis, Bloch-Floquet theorem, and full wave simulation. A demonstration of SE-CRLH structure is designed. The measurements are in agreement with simulations and theory.

1. INTRODUCTION

Dual-band devices have a wide range of applications in wireless communication systems [1, 2]. During the past decade, double negative metamaterials have received substantial attention in the scientific and engineering communities for its unique electromagnetic properties.

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In 2006, C. Caloz proposed dual composite right/left handed (D-CRLH) TL based on composite right/left handed (CRLH) TL for dual-band applications [3]. The D-CRLH TL indeed exhibits its lowpass band at lower frequencies and highpass band at higher frequencies and its natural stop-band is between the RH and LH band [4–7] in opposite to CRLH TL [8, 9]. Whereas D-CRLH TL can not be used for dual bandpass filter straight due to the lowpass and highpass characteristics of the first and second pass band, respectively. To further extend the dual-band applications, A. Rennings [10] presented extended composite right/left-handed (E-CRLH) TL, which exhibits dual-band bandpass characteristics and enabled nonzero cutoff frequency [11, 12]. However, the limitations of complicated structures and three broadband balanced conditions make E-CRLH TL difficult for engineering application.

In this work, a simplified extended composite right/left-handed TL with dual-band behavior is proposed. Compared with the E-CRLH structures, both the size and the structure complexity are reduced. More importantly, the design procedures are simplified because only two balanced conditions are required. And compared with the D-CRLH structures, the nonzero cut-off frequency is enabled by introducing an additional shunt inductance with negative permittivity effect. As a potential application to dual-band bandpass filter, each cutoff frequency and bandwidth are controllable by adjusting the values of elements. The physical structure is designed, fabricated and tested.

2. SIMPLIFIED EXTENDED CRLH TL

2.1. Equivalent Circuit and Physical Configuration

The symmetrical equivalent π-network of the proposed SE-CRLH TL unit is shown in Fig. 1(a). It can be seen that the series capacitor is taking away from the equivalent circuit model of the reference [10, 11]. The physical configuration of the proposed three stages SE-CRLH structure is shown in Fig. 1(b). The capacitance (C_D) and the inductance (L_D) of the series parallel resonance tank depend on the number of the interdigital finger and/or their gap width, and its closed stub size, respectively. The capacitance (C_S) and inductance (L_S) of the shunt series resonance tank depend on the dimension of the rectangular patch and the conjoint stub, respectively. The inductance (L_V) depends on the stub with metallic via hole. The series inductance (L_P) and shunt capacitance (C_P) attribute to the inherent parasitic RH effect. To further reduce the size of the SE-CRLH structure, the grounded stub is bended and connected with the common metallic via as shown in Fig. 1(b).

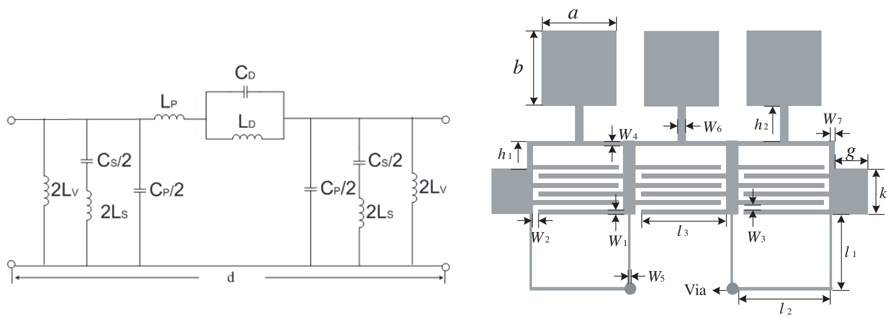


Figure 1. The proposed simplified E-CRLH TL. (a) Symmetrical equivalent π-network. (b) Layout of the SE-CRLH (three-stage). $a = 2.8\,\text{mm}$, $b = 3\,\text{mm}$, $h_1 = 0.4\,\text{mm}$, $h_2 = 1.6\,\text{mm}$, $k = 1.8\,\text{mm}$, $g = 2\,\text{mm}$, $l_1 = l_2 = 3\,\text{mm}$, $l_3 = 3.1\,\text{mm}$, $w_1 = w_2 = w_3 = w_4 = 0.2\,\text{mm}$, $w_5 = 0.1\,\text{mm}$, $w_6 = 0.2\,\text{mm}$, $w_7 = 0.1\,\text{mm}$.

2.2. Theory

The fundamental properties of SE-CRLH TL are straightforwardly analyzed by elementary TL theory and Bloch-Floquet theorem. To easily obtain dispersion relation of the periodic structure, the -network is changed to its corresponding ladder network [3, 4]. In the model, each parameter is extracted from the circuit and full wave simulation. When SE-CRLH TL is designed with the balanced condition which will be described in following, the extracted circuit parameters of one unit cell are $L_D = 0.82\,\text{nH}$, $C_D = 1.38\,\text{pF}$, $L_V = 4.52\,\text{nH}$, $L_S = 3.5\,\text{nH}$, $C_S = 0.32\,\text{pF}$, $L_P = 1.78\,\text{nH}$, $C_P = 0.81\,\text{pF}$, respectively. The series impedance $Z(\omega)$, shunt admittance $Y(\omega)$, and characteristic impedance $Z_c(\omega)$ are derived [3]

$$Z(\omega) = j\omega L_P \frac{\omega^2 - \omega_{Z0}^2}{\omega^2 - \omega_{Z\infty}^2} \quad Y(\omega) = jC_P \frac{(\omega^2 - \omega_{Y01}^2)(\omega^2 - \omega_{Y02}^2)}{\omega(\omega^2 - \omega_{Y\infty}^2)} \tag{1}$$

$$Z_c(\omega) = \sqrt{\frac{Z(\omega)}{Y(\omega)}} = \sqrt{\frac{L_P}{C_P}} \sqrt{\frac{\omega^2(\omega^2 - \omega_{Z0}^2)(\omega^2 - \omega_{Y\infty}^2)}{(\omega^2 - \omega_{Z\infty}^2)(\omega^2 - \omega_{Y01}^2)(\omega^2 - \omega_{Y02}^2)}} \tag{2}$$

$$\omega_{Z\infty} = \sqrt{\frac{1}{L_D C_D}}, \quad \omega_{Y\infty} = \sqrt{\frac{1}{L_S C_S}} \tag{3}$$

$$\omega_{Z0} = \sqrt{\frac{L_P + L_D}{C_D L_D L_P}}, \quad \omega_{Y0_{1,2}}^2 = \frac{M \pm \sqrt{M^2 - 4N}}{2N} \tag{4}$$

$$M = L_V C_P + L_S C_S + L_V C_S, \quad N = L_S C_S L_V C_P \tag{5}$$

The proposed SE-CRLH TL has two broadband balanced conditions. The RH-notched-LH balanced condition is given by

$$\omega_{Z\infty} = \omega_{Y\infty} = 4.6\,\text{GHz} \Rightarrow L_D C_D = L_S C_S \tag{6}$$

The LH-RH balanced condition is given by

$$\omega_{Z0} = \omega_{Y0_2} = 5.8\,\text{GHz} \tag{7}$$

From Equation (1) it is obvious that $\text{Im}(Z)$ values can be divided into three bounded regions by the critical frequency points of $\omega_{Z\infty}$ and ω_{Z0}. Similarly, $\text{Im}(Y)$ values have four bounded regions divided by $\omega_{Y\infty}$, ω_{Y01} and ω_{Y02}. Fig. 2 shows the imaginary values of the per-unit length impedance and admittance with the balanced conditions (6) and (7) versus frequency.

By applying the periodic boundary conditions related with Bloch-Floquet theorem to the unit cell, the dispersion relation is obtained as:

$$\beta = \frac{1}{d}\cos^{-1}\left(1 + \frac{ZY}{2}\right) \tag{8}$$

where β is propagation constant for Bloch waves and d is the periodicity of the structure. When $\omega = \omega_{Y01} = 2.3\,\text{GHz}$, $\beta = 0$. And below ω_{Y01}, β has complex numbers with imaginary values, it exhibits single negative permittivity properties. From Equation (8), when $ZY \in [-4, 0]$, β has purely real values, so it is corresponding to the passband in frequency response. While $ZY \in (-\infty, -4] \cup [0, +\infty)$, β has complex numbers with nonzero imaginary values, thus, it is corresponding to the stopband in frequency response as shown in Fig. 2.

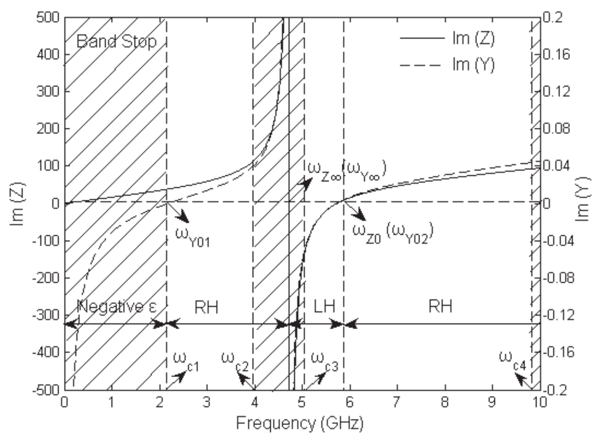


Figure 2. Imaginary value of Z and Y with fully balanced conditions

ω_{c1}, ω_{c2} are cut-off frequencies in the first RH region. ω_{c3}, ω_{c4} are cut-off frequencies in the LH and the second RH region. ω_{c2}, ω_{c3}, ω_{c4} are the roots of the formula $ZY = -4$ from Equations (1) and (2). The resulting equation is

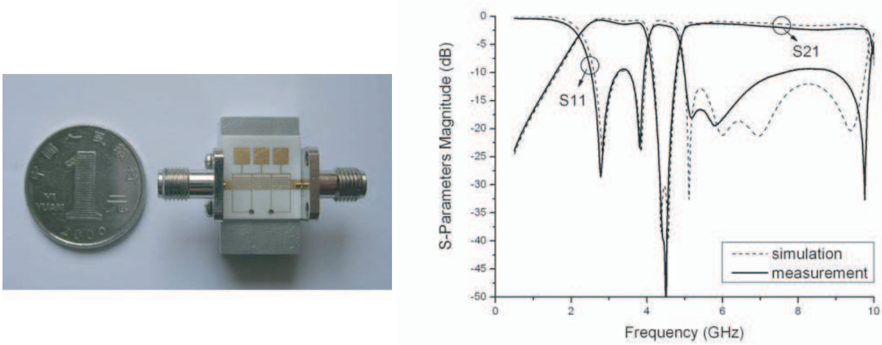
$$L_P C_P \omega^6 - L_P C_P \left(\omega_{Z0}^2 + \omega_{Y01}^2 + \omega_{Y02}^2\right)\omega^4 + \left[L_P C_P \omega_{Z0}^2 \omega_{Y01}^2 + L_P C_P \left(\omega_{Z0}^2 + \omega_{Y01}^2\right)\omega_{Y02}^2 + 4\left(\omega_{Z\infty}^2 + \omega_{Y\infty}^2\right) - 4\right]\omega^2 - L_P C_P \omega_{Z0}^2 \omega_{Y01}^2 \omega_{Y02}^2 - 4\omega_{Z\infty}^2 \omega_{Y\infty}^2 = 0 \quad (9)$$

Equation (9) is a cubic equation with respect to ω^2 and three roots of this equation can be obtained by Cardano's formula. The obtained cutoff frequencies (ω_{c2}, ω_{c3}, ω_{c4}) are 3.95 GHz, 5.05 GHz and 9.8 GHz. Note that ω_{c4} is the cutoff frequency in the second RH band.

3. SIMULATION AND EXPERIMENT

Figure 3(a) shows the top view of the fabricated three-stage SE-CRLH structure. It is composed of dielectric substrate with RO4003 $\varepsilon_r = 3.38$, height 0.813 mm, and golden coating with thickness 0.018 mm. The input and output ports are fabricated with 50 Ω coaxial connector. The width and length of feed line are optimized as 1.8 mm and 2 mm for 50 Ω Bloch impedance matching. As shown in Fig. 3(b), the results of S-parameters magnitude with full wave simulations and measurements are depicted. It exhibits dual-band bandpass characteristics. The cutoff frequencies of first passband are 2.3 GHz and 3.95 GHz. The cutoff frequencies of second passband are 5.05 GHz and 9.8 GHz. The insertion loss is less than 0.8 dB in first passband, less than 1.9 dB in second passband and more than 50 dB at the central of notched band. The return loss is better than 10 dB in the passbands. The measurement results contain the effect of coaxial connector and feed line.

Figure 4 shows the dispersion curves of the three-stage SE-CRLH TL by theory and measurement. The theoretical dispersion curves are from theory using (1), (2) and (8). The measured dispersion points are the measurement extracted without the influence of the feed lines from the transmission matrix analysis. Fig. 5 shows the Bloch impedance of the SE-CRLH structure by theory. It is analyzed by ABCD matrix in "Π" type equivalent circuit [13, 14]. Bloch impedance exhibits great changes at the vicinity of the first cutoff frequency due to the non-duality of shunt inductance L_V. In this work, 50 Ω feed line is chosen for the broadband impedance matching.



(a) (b)

Figure 3. (a) The top view of the fabricated three-stage SE-CRLH structure. (b) Simulation and measurement of frequency behavior.

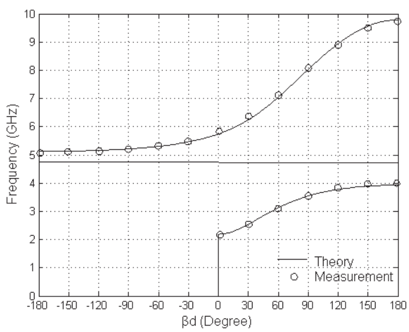


Figure 4. Dispersion curves of SE-CRLH structure.

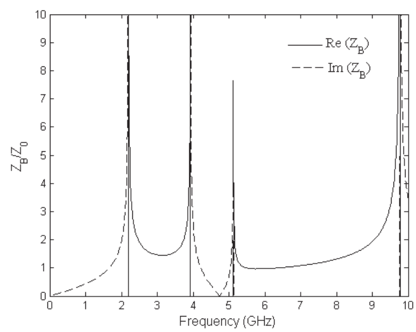


Figure 5. Bloch impedance. $Z_0 = 50\,\Omega$.

4. CONCLUSION

A simplified E-CRLH TL is proposed and its fundamental properties are investigated. Compared with E-CRLH structures, both the size and the structure complexity are reduced. Moreover, when the SE-CRLH structure is employed in dual-band bandpass filter, the design procedures are also simplified because only two broad balanced conditions are required.

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