A Compact Microstrip Low-Pass Filter Using D-CRLH Transmission Line with Ultra-Wide Stopband and High Selectivity

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Abstract. *A novel structure of dual-composite right/left-handed transmission line (D-CRLH TL) is proposed and analyzed in this paper. The simulated results show that there is a stopband between the first right-handed passband and the left-handed passband of the proposed D-CRLH TL. This stopband characteristic is applied to improve the electromagnetic performances of low-pass filter (LPF). A planar compact microstrip LPF with ultra-wide stopband (UWSB) and high selectivity is designed, fabricated and measured. The measured and simulated results are in good agreement with each other, indicating that this design method is effective and successful. The measured results show that the cut-off frequency of the LPF in this paper is 3.68 GHz, the stopband with insertion loss of more than 20 dB is from 3.84 GHz to 20.21 GHz (136.1 %), and the sharpness is 106.25 dB/GHz. Compared with the previous works of references, the LPF in this paper has less insertion loss, greater stop-bandwidth and better sharpness. Besides, this LPF also realizes a 73 % size reduction in comparison with the same work in reference [14].*

Keywords

Dual-composite right/left-handed transmission line (D-CRLH-TL), low-pass filter (LPF), ultra-wide stopband (UWSB), high selectivity, miniaturization.

1. Introduction

In 1968, metamaterial that exhibit both negative permittivity and negative permeability was first proposed by Veselago in theory [1]. In 2000, Smith and his co-workers realized this metamaterial experimentally by using split ring resonators and rods [2]. In 2002 and 2006, Caloz and Itoh proposed the equivalent circuit models of CRLH TL and D-CRLH TL respectively [3], [4]. The fast development of CRLH TL and D-CRLH TL provides new ways to design microwave instruments with good electromagnetic performances [5-9].

Microstrip low-pass filters (LPFs) play very important roles in modern microwave wireless communication systems, and the planar, compact LPFs with wide stopband and high selectivity are of increasing demand in RF and microwave communication systems with the development of microwave technology [10-13], [16]. Recently, three methods to design LPFs with wide stopband and a sharp cutoff frequency response have been reported: in reference [11], the lumped elements are used to improve the performances of LPFs, but this method is difficult to realize and control; in references [12], [13], electromagnetic band gap (EBG) and defected ground structure (DGS) are used to improve the performances of LPFs, although these LPFs have very good electromagnetic behaviors, the use of EBG and DGS leads to bulky filters (large in size) that are difficult to integrate; in reference [16], a new technology called Micromachine Technology, was used to improve the performances of LPFs, but this technology is difficult to realize, and the price of fabrication is very expensive.

In this paper, a novel structure of D-CRLH TL is proposed and analyzed, and the simulated results show that there is a stopband between the first right-handed passband and the left-handed passband. Then, the proposed D-CRLH TL is used to improve the performances of low-pass filter. The D-CRLH TL cells are embedded into the conventional LPF, and a planar compact LPF with UWSB and high selectivity is designed, fabricated and measured. The measured and simulated results are in good agreement with each other, showing that the cut-off frequency of this LPF is 3.68 GHz, the stopband with insertion loss of more than 20 dB is from 3.84 GHz to 20.21 GHz (the relative is 136.1 %), and the sharpness is 106.25 dB/GHz. Compared with the previous works reported in references [12-15], the LPF in this paper has less insertion loss, greater stop-bandwidth and better sharpness, and shows better electromagnetic performances. Besides, this LPF also realizes a 73 % size reduction in comparison with the same work in [14].

2. Analysis of OF D-CRLH-TL

2.1 Analysis in Theory

Fig. 1 is the basic equivalent circuit model of D-CRLH TL. It consists of a series circuit of left-handed capacitor (C_L) and right-handed inductor (L_R) in parallel and a shunt circuit of right-handed capacitor (C_R) and left-handed inductor (L_L) in series.

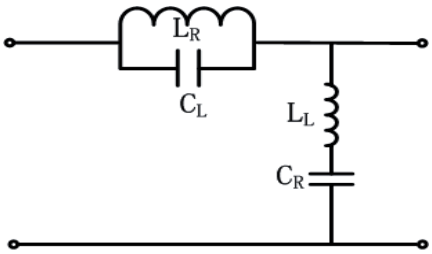


Fig. 1. Basic equivalent circuit model of D-CRLH TL.

The expressions of series impedance Z and shunt admittance Y of the basic equivalent circuit model are:

$$Z=\frac{1}{\frac{1}{j\omega L_R}+j\omega C_L}=\frac{j\omega L_R}{1-\omega^2 L_R C_L}=\frac{j\omega L_R}{1-\left(\omega/\omega_{se}\right)^2}, \quad (1)$$

$$Y=\frac{1}{\frac{1}{j\omega C_R}+j\omega L_L}=\frac{j\omega C_R}{1-\omega^2 L_L C_R}=\frac{j\omega C_R}{1-\left(\omega/\omega_{sh}\right)^2} \quad (2)$$

in which,

$$\omega_{se}=\frac{1}{\sqrt{L_R C_L}}, \quad \omega_{sh}=\frac{1}{\sqrt{L_L C_R}}. \quad (3)$$

According to the reference [17], the right/left-handed cut-off frequencies of D-CRLH-TL are:

$$\omega_{cR}=\omega_0\sqrt{\frac{[\kappa+1/(2\omega_R)^2]\omega_0^2-\sqrt{[\kappa+1/(2\omega_R)^2]^2\omega_0^4-4}}{2}}, \quad (4)$$

$$\omega_{cL}=\omega_0\sqrt{\frac{[\kappa+1/(2\omega_L)^2]\omega_0^2-\sqrt{[\kappa+1/(2\omega_L)^2]^2\omega_0^4-4}}{2}} \quad (5)$$

in which

$$\omega_R=\frac{1}{\sqrt{L_R C_R}}, \quad \omega_L=\frac{1}{\sqrt{L_L C_L}}, \quad (6)$$
$$\omega_0=\sqrt{\omega_{se}\omega_{sh}}, \quad \kappa=L_R C_L+L_L C_R.$$

When $\omega_{se}=\omega_{sh}=\omega_0$, the equivalent circuit model of D-CRLH-TL is under the balance condition, we can get the expressions (7),

$$\omega_R^2\omega_L^2=\frac{1}{L_R C_R L_L C_L}=\omega_{se}^2\omega_{sh}^2=\omega_0^4, \quad \kappa=\frac{2}{\omega_0^2}. \quad (7)$$

According to expressions (1-7), we can get a simple expression of the left/right-handed cutoff frequencies of D-CRLH TL, as shown in expression (8):

$$\begin{cases}\omega_{cL}=\omega_0\sqrt{1+\frac{\omega_L}{8\omega_R}+\sqrt{\frac{\omega_L}{4\omega_R}}\sqrt{1+\frac{\omega_L}{16\omega_R}}} \\ \omega_{cR}=\omega_0\sqrt{1+\frac{\omega_L}{8\omega_R}-\sqrt{\frac{\omega_L}{4\omega_R}}\sqrt{1+\frac{\omega_L}{16\omega_R}}}\end{cases} \quad (8)$$

According to expressions (7) and (8), when D-CRLH TL is under the balance condition, the left-handed and the right-handed cutoff frequencies are not equal with each other, just as $\omega_{cL}\neq\omega_{cR}$, so the stopband between the left-handed and the right-handed cutoff frequencies cannot be eliminated, and it will change with the change of ω_{cL} and ω_{cR}.

2.2 Analysis in Simulation

Fig. 2 is the structure of the proposed D-CRLH TL in this paper. This structure is designed on a substrate with relative dielectric constant 2.65 and thickness 0.8 mm. The physical dimensions of the unit cell are the first group shown in Tab. 1, and it is analyzed by Ansoft Designer, the simulated results are shown in Fig. 3.

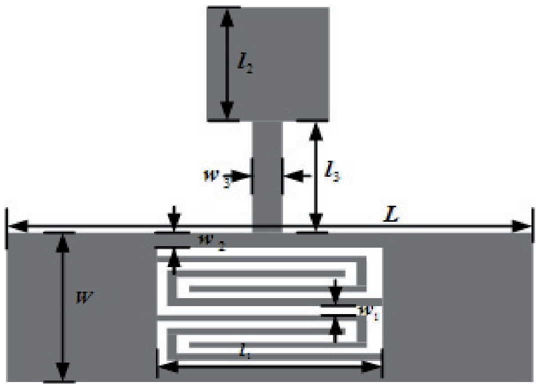
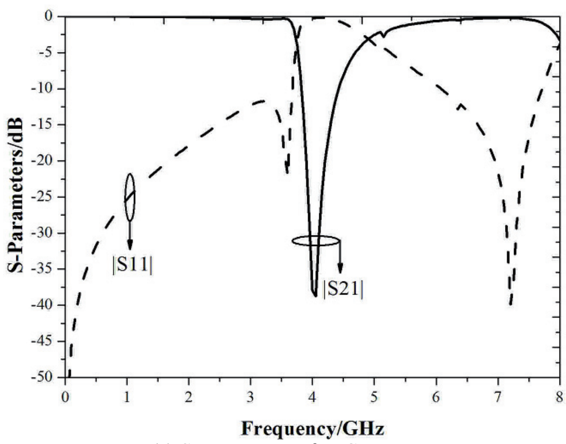


Fig. 2. The unit structure of the proposed D-CRLH TL.

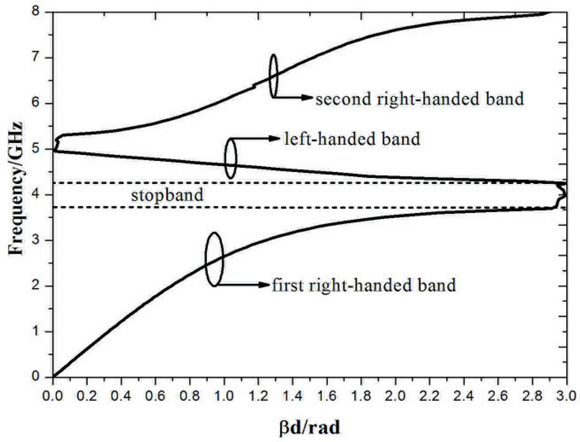
Fig. 3 is the simulated results of the proposed D-CRLH TL, it is shown that the right-handed cut-off frequency f_{cR} = 3.70 GHz, the left-handed cutoff frequency f_{cL} = 4.35 GHz, and there is a stopband between the first right-handed and left-handed passbands.

	L	*W*	*l*1	*l*2	*l*3	*w*1	*w*2	*w*3
unit1	7	2.2	5	3	3	0.25	0.1	0.2
unit2	6	2.2	4	2.5	2.5	0.25	0.1	0.2
unit3	5	2.2	3	2	2	0.25	0.1	0.2
unit4	3	2.2	1	1	1	0.25	0.1	0.2
unit5	3	2.2	1	1	1	0.25	0.1	0.2

Tab. 1. Physical dimensions of the 5 unit cells (unit: mm).



(a) S-parameters of D-CRLH-TL



(b) Dispersion of D-CRLH-TL

Fig. 3. The simulated results.

Fig. 4 is the simulated results of the 5 unit cells of D-CRLH-TL, whose physical dimensions are shown in Tab. 1.

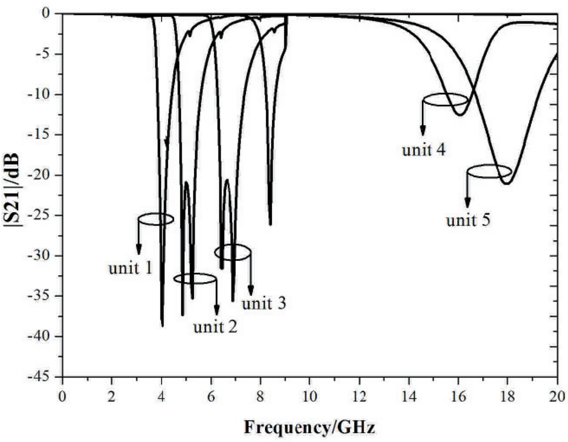


Fig. 4. Simulated results of the 5 unit cells of D-CRLH-TL.

The results in Fig. 4 indicate that the stopband will increase with the reduction of l_1 and l_2 ($l_2 = l_3$), so the stop-band can be controlled by changing the physical dimensions of D-CRLH TL. This special bandstop characteristic of D-CRLH TL can be used to improve the selectivity and the stopband characteristic of the Hi-lo microstrip low-pass filter.

3. Improved Design of the Proposed LPF

According to the design methods of the Butterworth Hi-lo microstrip low-pass filter in reference [14], we can get the basic physical dimensions of the designed LPF. When the high-impedance and low-impedance are equal to 116.7 Ω and 17.5 Ω, the physical dimensions $a = 3$ mm, $b = 4.3$ mm, in order to improve the selectivity and the stopband characteristic of the conventional Hi-lo microstrip LPF, the 5 D-CRLH TL cells are embedded into the Hi-lo microstrip LPF, and the structure of the LPF in this paper is shown in Fig. 5.

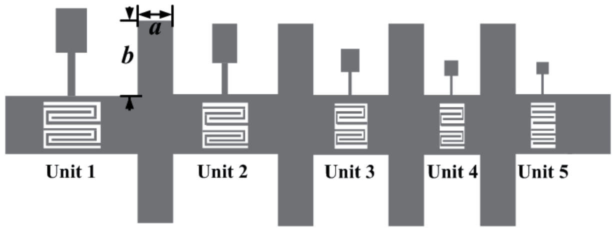


Fig. 5. The structure of the proposed LPF.

The physical dimensions of the 5 unit cells embedded into the Hi-lo microstrip LPF are shown in Tab.1.

	L	W	l_1	l_2	l_3	w_1	w_2	w_3
unit1	7	2.2	5	3	3	0.25	0.1	0.2
unit2	6	2.2	4	2.5	2.5	0.25	0.1	0.2
unit3	5	2.2	3	2	2	0.25	0.1	0.2
unit4	3	2.2	1	1	1	0.25	0.1	0.2
unit5	3	2.2	1	1	1	0.25	0.1	0.2

Tab. 1. Physical dimensions of the 5 unit cells (unit: mm).

The proposed LPF was simulated, fabricated and measured. The photograph of the fabricated LPF is shown in Fig. 6. The simulated and measured results are shown in Fig. 7. It can be seen from Fig. 7 that the measured and simulated results are in good agreement with each other.

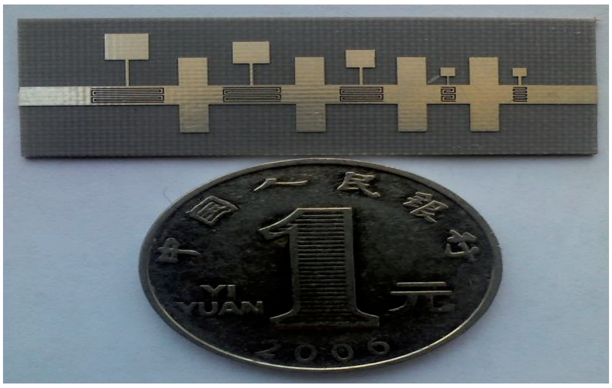


Fig. 6. The photograph of the designed LPF.

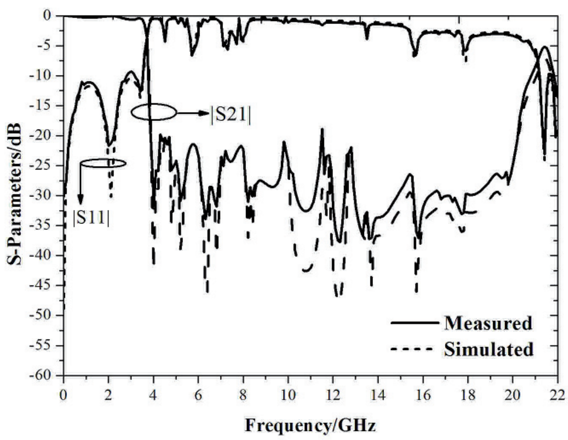


Fig. 7. The measured and simulated results.

In Fig. 7, the measured results show that the designed LPF in this paper has good electrical performances: in the passband, the 3-dB cut-off frequency is 3.68 GHz, the insertion loss is less than 0.40 dB, and the return loss is better than 10 dB; in the stopband, the stopband with insertion loss of more than 20 dB is from 3.84 GHz to 20.21 GHz (the relative is 136.1 %); the transition band between passband and stopband is only 0.16 GHz (the 3-dB cut-off frequency is 3.68 GHz and the frequency with insertion loss of more than 20 dB is 3.84 GHz), and the sharpness is 106.25 dB/GHz.

The comparison of the wide stopband LPFs between this paper and the same works in references is shown in Tab. 2.

LPFs	Insertion loss(dB)	Relative bandwidth	Sharpness (dB/GHz)
[12]	0.9	103.5%	48.6
[13]	0.51	76%	17
[14]	1.05	124.7%	22.9
[15]	0.1	100%	14.2
This paper	0.40	136.1%	106.25

Tab. 2. Comparison of the wide stopband LPFs.

It can be seen that compared with the same works in references [12-15], the LPF in this paper has less insertion loss, greater stop-bandwidth, and better sharpness, this LPF is the best. In addition, the designed LPF also realizes a 73 % size reduction in comparison with the previous work in reference [14] for the same substrate, which indicates that the designed LPF may realize miniaturization.

4. Conclusions

A planar compact low-pass filter with ultra-wide stopband and high selectivity is presented by using the stopband characteristic of the proposed D-CRLH TL in this paper. The characteristics of D-CRLH TL are analyzed in theory and simulation. Then, the designed LPF is simulated, fabricated and measured; the measured and simulated results are in good agreement, showing that the 3-dB cut-off frequency is 3.68 GHz; the stopband is from 3.84 GHz to 20.21 GHz (the relative is 136.1 %), and the sharpness is 106.25 dB/GHz. Compared with the previous works in references [12-15], the LPF in this paper has less insertion loss, greater stop-bandwidth, better sharpness, and it is the best. Besides, this LPF also realizes a 73 % size reduction in comparison with the same work in reference [14].

Acknowledgements

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