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COMPACT ULTRA-WIDEBAND BANDPASS FILTER WITH SHARP ATTENUATION USING MODIFIED COMPOSITE RIGHT/LEFT-HANDED TRANSMISSION LINES

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Abstract—In this paper, the characteristics of novel modified composite right/left-handed (CRLH) transmission lines are discussed, and an ultra-wideband (UWB) bandpass filter (BPF) using the modified CRLH transmission lines is presented. Design formulas of a novel modified CRLH unit cell are theoretically derived. Based on the design formulas, the UWB bandpass filter with three unit cells is designed, fabricated, and measured. The measurement results show that the UWB bandpass filter has an insertion loss of less than 1 dB, bandwidths of $2.9 \sim 49$ GHz, and a rejection of greater than 50 dB at 5.8 GHz.

1. INTRODUCTION

A bandpass filter (BPF) is an essential component in an ultra- wideband (UWB) system. Recently, many UWB BPFs have been proposed [1–6]. Some have been implemented using composite right/left-handed transmission lines [7–10] since left-handed transmission lines were introduced as meta-materials by Caloz and Itoh [11]. Numerous configurations of composite right/left-handed (CRLH) transmission lines have been proposed to facilitate a wide variety of UWB filters. Size reduction and bandwidth enhancement of a bandpass filter can be achieved by using the CRLH structure [12]. Obtaining good

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selectivity and out-of-band suppression is also very important. Sharp rejection characteristics at 5.8 GHz are needed to avoid interference between the UWB system and the wireless local area network (WLAN).

In this paper, a compact UWB bandpass filter using modified CRLH unit cells is implemented. The simulated and measured results are in good agreement. The experimental filter exhibits sharp rejection characteristics.

2. CIRCUIT DESIGN

2.1. Modified CRLH Structure

The modified CRLH structure is described by the circuit model shown in Figure 1. The right-handed series inductor, L_R, and shunt capacitor, C_R, and the left-handed shunt inductor, L_L and series capacitor, C_L, are similar to those of the conventional CRLH structure [13]. Otherwise in the conventional CRLH structure, the right-handed series inductor, L_R, and the left-handed series capacitor, C_L, are in parallel. The series impedance, shunt admittance, and complex propagation constant of the modified CRLH unit cell are as follows:

$$Z = \frac{1}{j\left(\omega C_L - 1/\omega L_R\right)} \tag{1}$$

$$Y = j\left(\omega C_R - \frac{1}{\omega L_L}\right) \tag{2}$$

$$\gamma = s(\omega)\sqrt{\frac{L_R}{L_L}}\sqrt{\frac{\left(\omega/\omega_{sh}\right)^2 - 1}{\left(\omega/\omega_{se}\right)^2 - 1}} \tag{3}$$

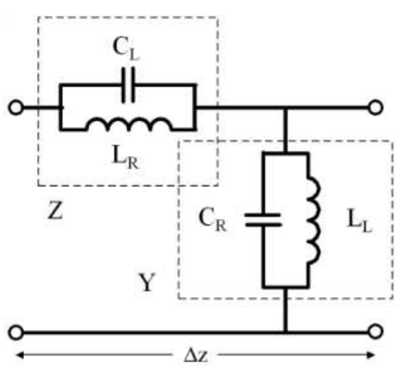


Figure 1. Circuit model of the modified CRLH unit cell.

where,

$$s(\omega) = \begin{cases} -1 & \text{if} \quad \omega_{se} < \omega_{sh} \quad LH\ range, \\ +1 & \text{if} \quad \omega_{se} > \omega_{sh} \quad RH\ range, \end{cases}$$

$$\omega_{se} = \frac{1}{\sqrt{L_R C_L}} \tag{4}$$

$$\omega_{sh} = \frac{1}{\sqrt{L_L C_R}} \tag{5}$$

$$\omega_0 = \sqrt{\omega_{se}\omega_{sh}}. \tag{6}$$

The characteristic impedance of the modified CRLH unit cell is as follows:

$$Z_0(\omega) = \frac{1}{\sqrt{C_L C_R}} \frac{\omega}{\sqrt{\left(\omega^2 - \omega_{se}^2\right)\left(\omega_{sh}^2 - \omega^2\right)}}. \tag{7}$$

Figure 2 shows the dispersions and attenuations of the modified CRLH unit cell. It becomes a series L and a shunt L below min(ω_{se}, ω_{sh}), and a series C and a shunt C above max(ω_{se}, ω_{sh}). Between min(ω_{se}, ω_{sh}) and max(ω_{se}, ω_{sh}), it becomes a series C and a shunt

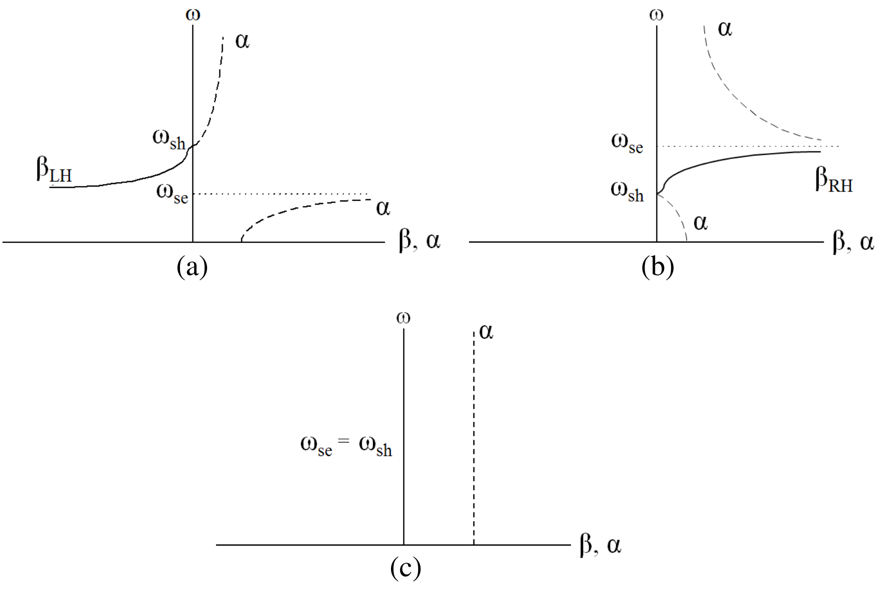


Figure 2. Dispersion and attenuation diagram of the modified CRLH unit cell: (a) $\omega_{se} < \omega_{sh}$, (b) $\omega_{sh} < \omega_{se}$, and (c) $\omega_{se} = \omega_{sh}$.

L ($\omega_{se} < \omega_{sh}$), or a series L and a shunt C ($\omega_{sh} < \omega_{se}$). Therefore, in the unbalanced case, the modified CRLH transmission line operates as a left-handed transmission line when $\omega_{se} < \omega_{sh}$, and as a right-handed transmission line when $\omega_{sh} < \omega_{se}$. In the balanced case, $\omega_{se} = \omega_{sh}$, it operates in the non-propagating mode. The characteristic impedances of the modified CRLH unit cell are shown in Figure 3. In the passband, the characteristic impedance is real, while it becomes imaginary in the stopband when the modified CRLH unit cell is operating in the unbalanced case, and it is matched to the port impedance R_0 at ω_0. The modified CRLH unit cell has no real characteristic impedance and all-stop frequency response in the balanced case.

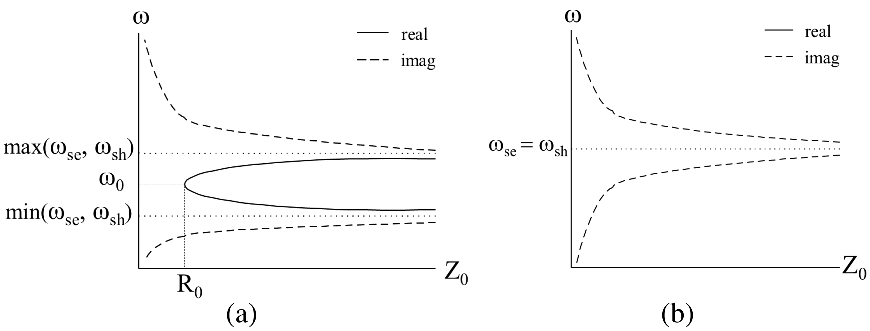
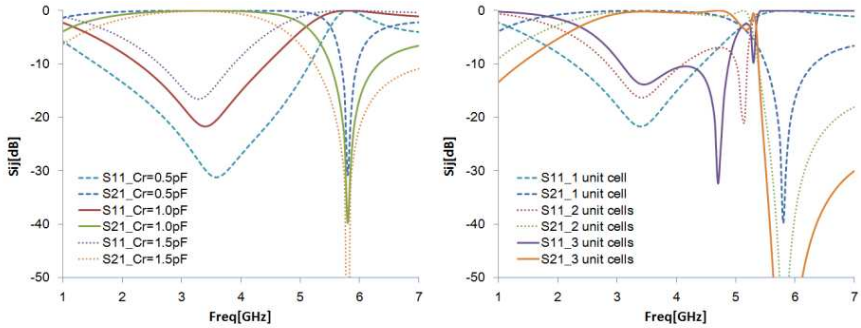


Figure 3. Characteristic impedances of the modified CRLH unit cell: (a) $\omega_{se} \neq \omega_{sh}$, and (b) $\omega_{se} = \omega_{sh}$.

2.2. LC Implementation of the UWB Bandpass Filter with a Modified CRLH Structure

The modified CRLH structure has a controllable passband and sharp attenuation characteristics in the stopband. Thus, we can use it to design a UWB BPF with a sharp rejection skirt. According to Eqs. (4), (5), and (7), we can calculate the element values of the modified CRLH unit cell. We have one degree of the freedom among 4 element values. C_R determines the slope parameter of the shunt resonator that makes the passband of the UWB BPF. Therefore, we selected C_R as a free variable element. Figure 4(a) shows single unit cell characteristics with $C_R = 0.5$, 1, 1.5 pF. When the lower edge frequency of the UWB BPF, f_{sh}, is 2.9 GHz, the attenuation pole frequency, f_{se}, is 5.8 GHz, and the characteristic impedance of the modified CRLH unit cell, Z_0, is 50 Ω at $f_0 = 4.1$ GHz, the element values are $L_R = 0.31$, 0.625, 0.94 nH, $L_L = 6.02$, 3.01, 2.0 nH, and



(a) (b)

Figure 4. LC implementation of the UWB BPF with the modified CRLH structure: (a) single unit cell characteristics with different C_R's, and (b) multiple unit cell characteristics with $C_R = 1\,\text{pF}$.

$C_L = 2.4$, 1.2, 0.8 pF, respectively. Figure 4(b) shows multiple unit cell characteristics with $C_R = 1\,\text{pF}$.

3. SIMULATION AND MEASUREMENT RESULTS

The UWB bandpass filter using the modified CRLH transmission lines is implemented on a 0.787-mm-thick Taconic TLX-9 substrate with a dielectric constant of 2.5 and a loss tangent of less than 0.002. Figure 5 shows the fabricated UWB bandpass filter, in which C_L is realized by inter-digital capacitor and L_L is realized by short circuited stub, while L_R and C_R are implemented by the main transmission line. With the aid of CST Microwave Studio, the dimensions of the structure can be optimized to be $w_1 = 2.2\,\text{mm}$, $w_2 = 1\,\text{mm}$, $l_1 = 8.5\,\text{mm}$, $l_2 = 7.5\,\text{mm}$, $l_3 = 7\,\text{mm}$, $l_4 = 6.5\,\text{mm}$, $l_5 = 4\,\text{mm}$, $l_6 = 4\,\text{mm}$,

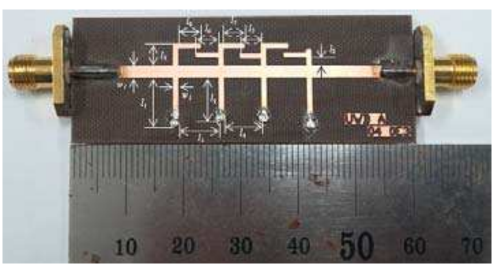


Figure 5. Photograph of the fabricated UWB BPF.

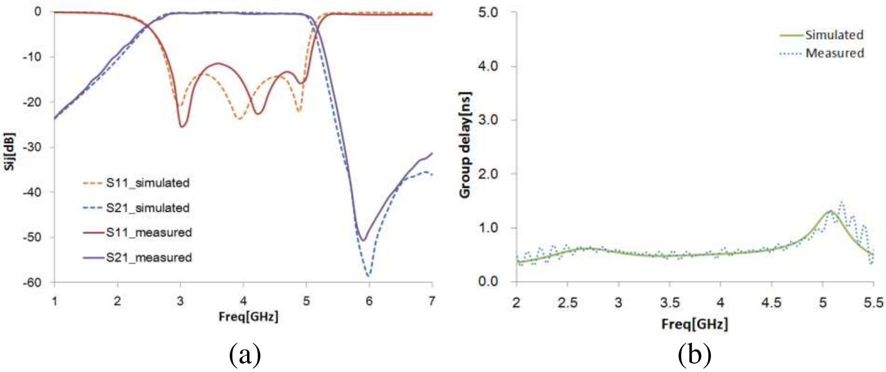


Figure 6. Simulated and measured frequency responses of the novel UWB BPF. (a) Wideband amplitude response. (b) Group delay.

$l_7 = 3.75$ mm, and $l_8 = 1.4$ mm. The size of the fabricated UWB BPF is $24.5 \times 14.7\,\text{mm}^2$. The measurements are carried out by using an Anritsu 37347C vector network analyzer. Figure 6(a) shows the measured results of the fabricated filter against the electro-magnetic (EM) simulated results. EM simulated and measured results show good agreement. The measured results show an insertion loss less than 1 dB in the passband ranging from 2.9 to 4.9 GHz, as well as a rejection of larger than 50 dB in the upper stopband of 5.8 GHz. The simulated and measured group delays of the filter are drawn in Figure 6(b), and the measured one is less than 0.9 ns within the passband and has a

Table 1. Comparison of UWB bandpass filters.

Reference	[5]	[7]	[9]	This work
Frequency [GHz]	3.4–4.8	2.465–5.222	3.22–4.61	2.9–4.9
Fractional Bandwidth [%]	34.15	71.73	35.51	51.28
Max. Insertion Loss [dB]	2.8	2	1.2	1
Attenuation at 5.8 GHz [dB]	35	15	70	50
Filter Size [mm^2]	28×20	16×4.6	23.8×8	24.5×14.7
Number of Layers	1	1	3	1

small in-band group-delay variation of not more than 0.5 ns indicating a good linearity of the proposed UWB BPF. The fabricated UWB BPF has better insertion loss and attenuation than the previous works of Refs. [5, 7]. It is compact compared with the size of Ref. [5] and has a simple structure of a single layer compared with Ref. [9], in which the UWB BPF is implemented by a three-layered structure for PCB fabrication. Table 1 shows the performance comparison of this work and the previous works.

4. CONCLUSION

This paper proposes a novel modified CRLH structure that has a continuous characteristic impedance distribution inside the passband, and sharp skirt characteristics in the upper or lower stopband whether the CRLH unit cell is right- or left-handed. The proposed CRLH structure is used to design and fabricate a UWB bandpass filter. The measured results show good agreement with the EM simulation results. This filter is compact and has a sharp rejection characteristic that is useful for avoiding the interference between the UWB and WLAN systems.

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