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COMPACT UWB BAND-PASS FILTER UTILIZING MODIFIED COMPOSITE RIGHT/LEFT-HANDED STRUCTURE WITH CROSS COUPLING

J.-Q. Huang and Q.-X. Chu

School of Electronic and Information Engineering
South China University of Technology
Guangzhou 510640, China

Abstract—An ultra wide band (UWB) band-pass filter (BPF) utilizing one modified composite-right/left-handed (CRLH) unit cell is proposed. By introducing the capacitive cross coupling to the traditional CRLH structure, the phase shift in the right-handed pass-band can be controlled, meanwhile, the cross coupling has negligible effect on the left-handed pass-band. The appropriate cross coupling can create three controllable transmission zeros. Thus, an UWB BPF with high selectivity is developed using only one unit cell, which leads to low insertion loss (less than 1.35 dB) and compact size ($0.47\lambda_0 \times 0.28\lambda_0$). The fabricated filter exhibits a rejection level higher than 20 dB at the stop-band from 11.95–16 GHz and flat group delay across the pass-band.

1. INTRODUCTION

Left-handed (LH) transmission lines (TLs) were proposed by Caloz and Itoh [1], Iyer and Eleftheriades [2], and Oliner [3] at almost the same time. A practical LH TL should be considered as the composite right/left-handed (CRLH) TL because of the line parasitics. Recently, numerous novel configurations of CRLH TL were proposed to facilitate a wide variety of microwave circuit application [4–10]. Size reduction and bandwidth enhancement of a band-pass filter (BPF) can be achieved by using the CRLH structure [11]. In order to obtain good selectivity and out-of-band suppression, more than one unit cell are usually engaged in the BPF. However, the insertion loss and size of the BPF will increase rapidly as more cells are used. In [12],

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Corresponding author: J.-Q. Huang (huang.jq02@mail.scut.edu.cn).

a series of super-wide BPFs with 3-dB FBW about of 72% were fabricated at different frequency bands by using two CRLH unit cells, whereas the insertion losses of these filters are about of 2.6 dB. Four simplified composite-right/left-handed (SCRLH) unit cells combining with embedded open-circuited stubs were employed to realize a UWB BPF with a widened upper stop-band in [13]. However, the size of this BPF is up to $1.1\lambda_0$ by $0.235\lambda_0$ (λ_0 is the guided wavelength at centre frequency of 6.85 GHz).

In this paper, a novel ultra wide band (UWB) BPF using one modified CRLH unit cell with the cross coupling is presented. The phase shift of the modified CRLH structure in the right-handed pass-band can be controlled by adjusting the cross coupling capacitor, which has negligible effect on the left-handed pass-band. Besides, the proper cross coupling will create three controllable transmission zeros. Thus, a UWB BPF with steep roll-off was constituted of only one CRLH unit cell, which results in very compact size and low insertion loss.

2. DESIGN OF UWB BPF

2.1. Modified CRLH Structure

The modified CRLH structure is described by the circuit model as shown in Figure 1. The LH shunt inductance L_L and series capacitor C_L, the RH shunt C_R and series inductance L_R are similar to those of the conventional CRLH structure. An additional cross-coupled capacitance C_g is introduced to create some novel characteristics.

According the ABCD matrix corresponding to the circuit model of modified CRLH unit cell, the analysis can be done through the Bloch theory [14].

$$\alpha + j\beta = \frac{1}{p}\cosh^{-1}(A) \tag{1}$$

where α and β are the attenuation and phase shift constant of the CRLH TL structure respectively, p is the length of the unit cell, and

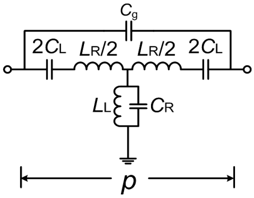

Figure 1. Circuit model of the modified CRLH TL unit cell.

A is the first element of ABCD matrix of the unit cell.

$$A = 1 - \frac{0.5\left(1-\omega^2 C_L L_R\right)\left(1-\omega^2 L_L C_R\right) C_L L_L}{\omega^2 C_L^2 L_L^2 - C_g L_L [0.25\left(1-\omega^2 C_L L_R\right)^2 \left(1-\omega^2 L_L C_R\right) - \left(1-\omega^2 C_L L_R\right)\omega^2 C_L L_L]} \tag{2}$$

Figure 2 shows the dispersions and attenuations of the modified CRLH unit cell. As the cross coupled capacitor C_g is increased from 0 to 0.2 pF under the case of $C_L = 0.40$ pF, $L_L = 1.0$ nH, $L_R = 1.625$ nH, $C_R = 0.65$ pF, the phase shift of the unit cell in the right-handed pass-band increases, meanwhile, C_g has little effect on the left-handed pass-band. It can also be observed that the bandwidth of the right-handed pass-band will decrease when C_g is increased.

Since the circuit model is symmetrical, the even- and odd-mode methods can be used to analyze its transmission zero of the CRLH unit cell [15]. The even- and odd-mode input impedances, Z_{even} and Z_{odd}, are expressed as

$$Z_{even} = \frac{j[(\omega^2 L_R C_L - 1)(\omega^2 L_L C_R - 1) - 4\omega^2 L_L C_L]}{2\omega C_L(\omega^2 L_L C_R - 1)} \tag{3}$$

$$Z_{odd} = \frac{j(\omega^2 L_R C_L - 1)}{2\omega[C_L - C_g(\omega^2 L_R C_L - 1)]} \tag{4}$$

So the transfer function S_{21} can be written as

$$S21 = \frac{(Z_{even} - Z_{odd})Z_0}{(Z_{even} + Z_0)(Z_{odd} + Z_0)} \tag{5}$$

where Z_0 is the impedance of the input/output port. The transmission-zero is created when S_{21} is equal to zero, i.e.,

$$Z_{even} = Z_{odd} \tag{6}$$

By using Equation (6), the location of transmission zero may be predicted.

Figure 3 shows the simulated results of the CRLH unit cell for various cross-coupled capacitance C_g under the case of $C_L = 0.32$ pF, $L_L = 1.728$ nH, $L_R = 1.254$ nH, $C_R = 0.38$ pF. It can be seen that a transmission zero at low pass-band is created by introducing C_g. As C_g increases, this transmission zero will move toward the higher frequency slightly. Besides, two transmission zeros are created when the proper cross-coupled capacitor is chose. These two transmission zeros will be relocated by adjusting the cross coupling. So far, three controllable transmission zeros can be created by introducing the cross-coupled capacitance C_g to the CRLH unit cell. By suitably tuning the parameters of the unit cell, an ultra wide band-pass filter with a good selectivity can be developed.

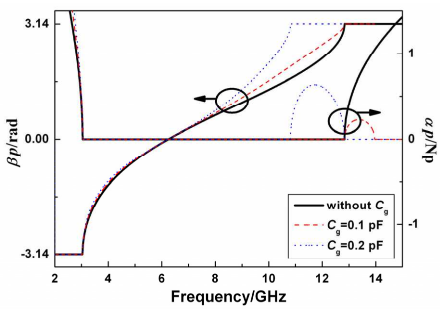

Figure 2. Dispersions and attenuations diagram of the modified CRLH TL unit cell with various C_g.

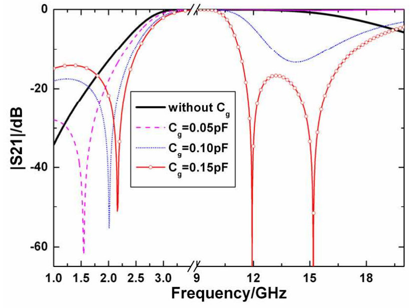

Figure 3. Simulated $|S_{21}|$ of the modified CRLH unit cell with various C_g.

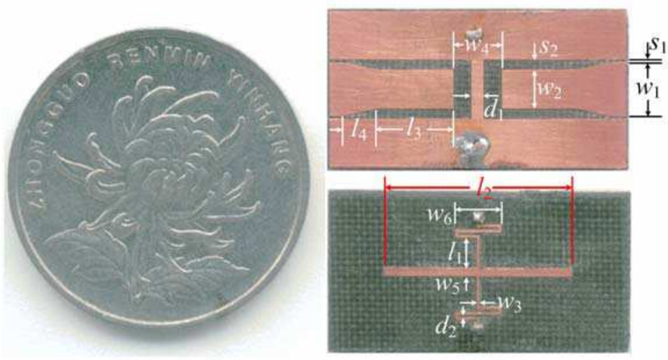

Figure 4. Photograph of the fabricated UWB BPF: (a) top view and (b) bottom view. ($s_1 = 0.22$ mm, $s_2 = 0.87$ mm, $w_1 = 4.5$ mm, $w_2 = 3.2$ mm, $w_3 = 0.22$ mm, $w_4 = 4$ mm, $w_5 = 0.7$ mm, $w_6 = 4$ mm, $l_1 = 2.5$ mm, $l_2 = 15$ mm, $l_3 = 6.25$ mm, $l_4 = 3$ mm, $d_1 = 1$ mm and $d_2 = 0.22$ mm)

2.2. UWB BPF Based on the CRLH Structure

The proposed UWB BPF based on the modified CRLH structure is implemented on a substrate with $\varepsilon_r = 2.55$, $\tan\delta = 0.0019$, and thickness $h = 0.8$ mm, as shown in Figure 4. It consists of a segment of coplanar waveguide (CPW), a metal plate and a pair of high impedance meander lines on the other side. The CPW signal line is divided by the ground and paralleled by the metal plate which connected to the ground via a pair of high impedance meander lines. Surface-to-surface coupling between the metal plate and signal line of CPW provides the

LH series capacitance C_L, while the pair of high impedance meander lines generates the LH shunt inductance L_L. Both C_R and L_R are due to the RH parasitic effects. The capacitive coupling between both signal lines is modeled as the cross-coupled capacitance C_g. All the parameters have the definite relation to the physical dimensions of the BPF, and thus their frequency responses can be controlled easily [16].

Figure 5 illustrates the EM-simulated S_{21} of UWB BPFs with different dimensions, e.g., w_4, w_5 and w_6. Results show that the bandwidth of the filter increases when w_5 is increased from 0.7 to 2.1 mm, as illustrated in Figure 5(a). On the other hand, the fractional bandwidth observably decreases when w_6 is increased from 2.0 to 1.0 mm, while the transmission zero at low band is shifted a little to lower frequency, as demonstrated in Figure 5(b). Furthermore, when w_4 is decreased from 4 to 2 mm, the first transmission zero

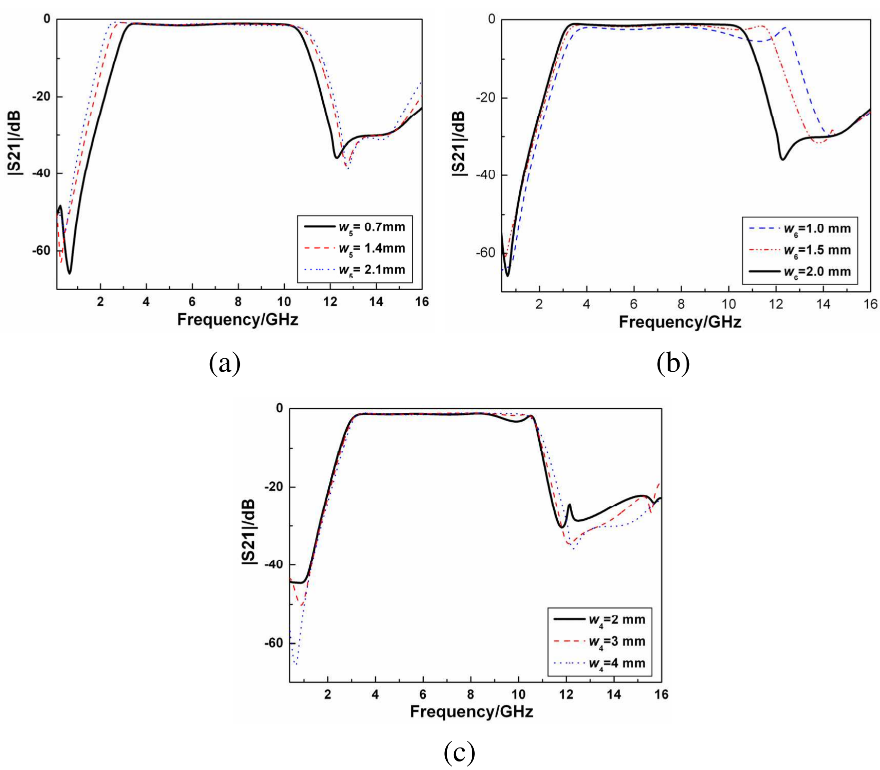

Figure 5. Full-wave simulated insertion loss of the UWB BPF. (a) Band-width of the BPF with various w_5 and (b) w_6, (c) selectivity of BPF with various w_4.

above the UWB band is changed from 12.27 to 11.83 GHz, and the transmission zero at low band is shifted a little to high frequency, as shown in Figure 5(c). These results demonstrate that the passband and selectivity of the proposed filter are flexible and can be controlled easily.

3. FABRICATION AND MEASUREMENT

With the aid of Ansoft HFSS, the dimensions of the structure can be optimized to be $s_1 = 0.22$ mm, $s_2 = 0.87$ mm, $w_1 = 4.5$ mm, $w_2 = 3.2$ mm, $w_3 = 0.22$ mm, $w_4 = 4$ mm,$w_5 = 0.7$ mm, $w_6 = 4$ mm, $l_1 = 2.5$ mm, $l_2 = 15$ mm, $l_3 = 6.25$ mm, $l_4 = 3$ mm, $d_1 = 1$ mm and $d_2 = 0.22$ mm. Figure 6 depicts the comparison of full-wave simulated S_{21} of the proposed UWB BPF against this shown in Ref. [13]. It can be observed that the proposed UWB BPF with compacter size has steeper roll-off than that of Ref. [13], owning to the cross coupling of modified CRLH structure.

The measurements are carried out by using Agilent vector analyzer N5230A. Figure 7 shows the measured results of the fabricated filter against the full-wave and equivalent circuit model simulated results. The parameters of equivalent circuit model are labeled as $C_L = 0.32$ pF, $L_L = 1.728$ nH, $C_R = 0.38$ pF, $L_R = 1.254$ nH, $C_g = 0.337$ pF. A good agreement between equivalent circuit, full-wave simulated and measured results has been achieved. The measured results show an insertion loss less than 1.35 dB in the pass-band ranging from 3.1 to 10.6 GHz, as well as a rejection of larger than 20 dB in the upper

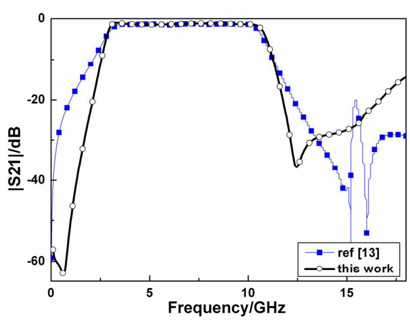

Figure 6. Comparison of the simulated $|S_{21}|$ of the proposed UWB BPF against that shown in Ref. [13].

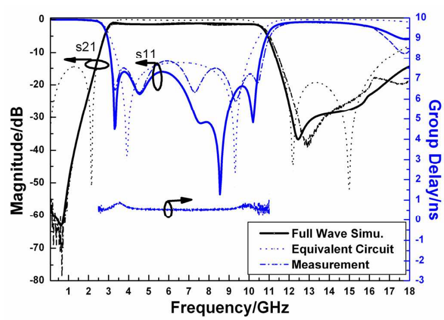

Figure 7. The frequency responses of simulation in full-wave and equivalent circuit model and measurement of the fabricated UWB BPF.

stop-band of 11.95–16 GHz. Moreover, the implemented filter with the feeding lines and SMA transform connector exhibits a flat group delay response below 0.85 ns. The maximum in-band variation of about 0.36 ns in the group delay implies good linearity of proposed UWB BPF, as illustrated in Figure 7.

4. CONCLUSION

A compact UWB BPF has been developed using only one modified CRLH unit cell. The proposed BPF has steep roll-off due to three transmission zeros created by the cross coupling. The fabricated UWB BPF is demonstrated to have a measured insertion loss less than 1.35 dB in the UWB band with a compact size of $0.47\lambda_0 \times 0.28\lambda_0$. Simulation and measurement reveal that the BPF has good suppressing in upper stop-band.

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