Progress In Electromagnetics Research Letters, Vol. 29, 107–113, 2012

5.8-GHZ SUPPRESSED UWB BANDPASS FILTER EMPLOYING MODIFIED CRLH-TL OF TWO AND THREE UNIT CELLS

Y. Z. Shen* and C. L. Law

School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore 639798, Singapore

Abstract—This paper presents a novel modified composite right/left-handed (CRLH) unit cell to achieve sharp rejection at 5.8 GHz. Design formulas are theoretically derived and numerically verified. Based on this unit cell, ultra-wideband (UWB) bandpass filters with two and three cells are designed, fabricated, and on-wafer measured. The measurement results show that the CRLH bandpass filter has a rejection of > 60 dB at 5.8 GHz, a minimum insertion loss of 1.1 dB, and 3-dB bandwidths of 3.09–4.79 GHz and 3.22–4.61 GHz for the two and three unit cells, respectively.

1. INTRODUCTION

A bandpass filter is an essential component in an ultra-wideband (UWB) system. Recently, many UWB bandpass filters with excellent performance have been reported [1–5]. One of these filters is based on the composite right/left-handed (CRLH) transmission line (TL) theory [6]. These CRLH filters are usually with compact size and good pass-band performance [6–8]. However, the stop-band performance, which is also very important, is seldom studied. For example, a UWB bandpass filter with a sharp rejection skirt at 5.8 GHz is needed to alleviate the interference between the UWB system and the wireless local area network (WLAN).

In this paper, by proposing a modified CRLH unit cell with high rejection at 5.8 GHz, two novel bandpass filters for lower UWB band applications are designed and implemented using metal-insulator-metal (MIM) capacitors [9, 10].

Received 2 December 2011, Accepted 16 January 2012, Scheduled 20 January 2012
* Corresponding author: Yi Zhu Shen (sh0001hu@ntu.edu.sg).

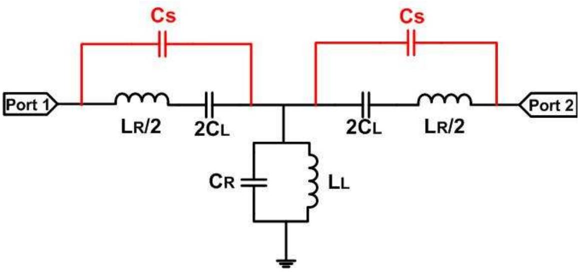


Figure 1. Circuit schematic of the proposed CRLH unit cell with C_S.

2. CRLH UNIT CELL DESIGN

2.1. Circuit Model and Analysis

As shown in Figure 1, a conventional CRLH unit cell is a symmetric T-network without C_S. It is composed of two identical impedance branches of $L_R/2$ and $2C_L$, and an admittance branch of C_R and L_L. The balanced case ($\omega_{se} = \omega_{sh}$) is chosen to facilitate the wideband impedance matching, where $\omega_{se} = 1/\sqrt{L_R C_L}$ and $\omega_{sh} = 1/\sqrt{L_L C_R}$ are the resonant angular frequencies of the impedance and admittance branches, respectively. Following the design guidelines in [6], setting two cutoff frequencies in (1) as 3.2 GHz and 5.27 GHz, where $\omega_L = 1\sqrt{L_L C_L}$ and $\omega_R = 1/\sqrt{L_R C_R}$, and letting the matching condition as $\sqrt{L_R/C_R} = \sqrt{L_L/C_L} = 50\,\Omega$, the values of this CRLH unit cell are derived as $L_R = 7.5\,\text{nH}$, $C_L = 0.2\,\text{pF}$, $L_L = 0.47\,\text{nH}$, and $C_R = 3.18\,\text{pF}$.

$$\omega_C = \omega_R \left| 1 \pm \sqrt{1 + \omega_L/\omega_R} \right|, \tag{1}$$

Then two capacitors C_S are added to constitute a modified unit cell. The C_S, $L_R/2$, and $2C_L$ form a branch with impedance

$$Z = \left(j\omega C_S + \left(j\omega \frac{L_R}{2} + \frac{1}{j\omega 2C_L} \right)^{-1} \right)^{-1}. \tag{2}$$

Theoretically, when $Z = \infty$, this modified branch can be used to obtain a high rejection at a specified angular frequency ω_{rej}. The required C_S can be evaluated as,

$$C_S = \frac{2C_L}{\omega_{rej}^2 L_R C_L - 1} = \frac{2C_L}{(\omega_{rej}/\omega_{se})^2 - 1}. \tag{3}$$

Letting $\omega_{rej} = 2\pi \times 5.8 \times 10^9\,\text{rad/s}$, and without changing L_R and C_L, $C_S = 0.4\,\text{pF}$ is obtained using (3).

It is interesting to note from (2) that the impedance of $Z = 0$ still occurs at $\omega_{se} = 1/\sqrt{L_R C_L}$, independent of C_S. Therefore, the modified CRLH unit cell is still a balanced structure and hence retaining the flat pass band frequency response characteristics. The cutoff frequencies of this proposed CRLH unit cell are derived as

$$\omega_{C\_\text{Modified}} = \omega_R \left(\frac{\left| \omega_L/\omega_R + 2K \pm 2\left(\omega_L/\omega_R + K^2\right)^{1/2} \right|}{1 + 4K\omega_R^2/\omega_{rej}^2} \right)^{1/2}, \quad (4)$$

where $\omega_0 = \sqrt{\omega_{se}\omega_{sh}}$ and $K = \omega_{rej}^2/(\omega_{rej}^2 - \omega_0^2)$. Note that (1) is the special case of (4) when $\omega_{rej} = \infty$, i.e., $C_S = 0$. With 5.8 GHz rejection frequency, the modified unit cell cutoff frequencies are 3.06 GHz and 4.95 GHz, respectively.

2.2. Circuit Simulation

To verify the above theoretical analysis, circuit schematic simulation is carried out using Agilent ADS. S parameters of the CRLH unit cell with and without C_S are obtained and shown in Figure 2. The curves clearly demonstrate that, by adding the capacitors C_S, a transmission pole and high rejection are achieved at 5.8 GHz.

Figure 3 presents the dispersion and attenuation behavior retrieved from $ABCD$ matrix [6], using the Bloch theory, where p is the length of the unit cell. The left-handed and right-handed regions of the modified CRLH structure are 3.06–4.1 GHz, and 4.1–4.95 GHz, respectively. There is no frequency gap between these two regions, i.e., the proposed one is still a balanced case. Moreover, the two cutoff

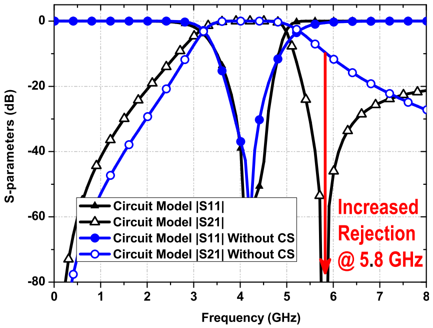


Figure 2. Simulated S parameters of the CRLH unit cell with and without C_S.

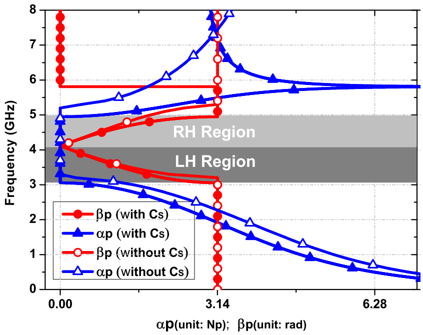


Figure 3. Dispersion/attenuation diagram of the proposed CRLH structure.

frequencies are 3.06 GHz and 4.95 GHz, respectively. They are the same as the theoretical results predicted using (4).

2.3. Multilayered Configuration

The proposed CRLH unit cell is implemented by a three-layered structure for PCB fabrication and illustrated in Figure 4. The layout is symmetrical along the AA' line. The inductor $L_R/2$ is realized by a microstrip line on the top layer (metal #1 layer) with a length of 4.7 mm and width of 0.1 mm, and the inductor L_L is represented by a short-circuited stub in the middle layer (metal #2 layer) with length and width of 1.2 mm and 0.1 mm, respectively. It should be noted that, to reduce the fabrication cost, a through-hole via (from metal #1 to metal #3 layers) rather than a blind via (from metal #2 to metal #3 layers) is used to form the short-circuited stub.

The capacitors are implemented by MIM structures which are with higher Q factor compared with the interdigital ones [9]. It therefore reduces the insertion loss of the CRLH bandpass filter. The capacitor $2C_L$ is realized by the top and middle overlapped layers with a size of $1.2 \times 1.2\,\mathrm{mm}^2$. Similarly, C_R is implemented by the overlapped area of

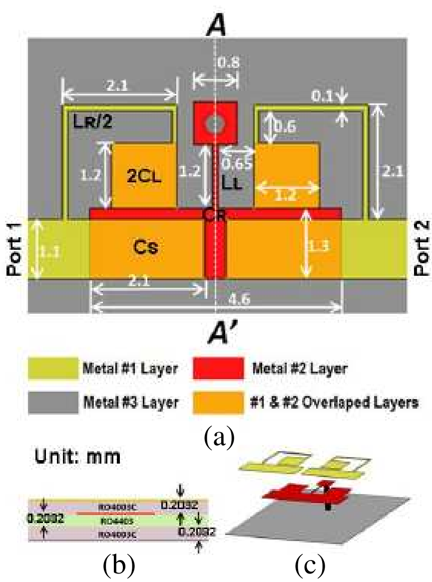


Figure 4. Illustration of the unit cell of proposed CRLH UWB bandpass filter. (a) Top view (it is symmetrical along the AA' line), (b) cross sectional view, and (c) 3-D explored view.

middle and bottom metal layers, with a rectangle of $1.3 \times 4.6\,\mathrm{mm}^2$ and two squares of $1.2 \times 1.2\,\mathrm{mm}^2$. Meanwhile, C_S is presented by part of the feedline, which is a rectangle overlapped between top and middle layers with size of $1.1 \times 2.1\,\mathrm{mm}^2$.

Figure 4(b) shows the cross sectional view of the three-layered configuration. Two different substrates, i.e., Rogers RO4003C ($\epsilon_r = 3.38$) and RO4403 ($\epsilon_r = 3.55$), with same thickness of 0.2032 mm are employed in the design. This configuration facilitates the PCB fabrications. The explored 3D view of the CRLH unit cell is depicted in Figure 4(c) for easy understanding.

Ansoft HFSS is employed to validate the three-layered structure. As shown in Figure 5, good agreement between ADS circuit model (in Figure 1) and HFSS simulation is obtained except in the frequency band above the rejection frequency of 5.8 GHz. The discrepancy between HFSS and ADS simulation results above 5.8 GHz is mainly due to the transmission line mode of the middle conductor strip, while the difference below 5.8 GHz is due to the parasitic of the inductors and the through-hole via which are not accounted for in ADS simulation.

3. MEASURED RESULTS AND DISCUSSIONS

The above studied CRLH unit cell has inherent bandpass characteristics. Identical unit cells can be periodically cascaded to form a UWB bandpass filter. Based on the proposed CRLH unit cell, two CRLH UWB bandpass filters with two and three unit cells are optimized, fabricated, and shown in Figure 6. To facilitate the on-wafer measurement, the microstrip feedline is transformed to a conductor-backed

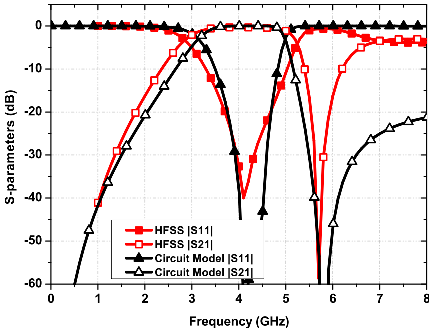


Figure 5. Simulated (HFSS and ADS) S parameters of the modified unit cell.

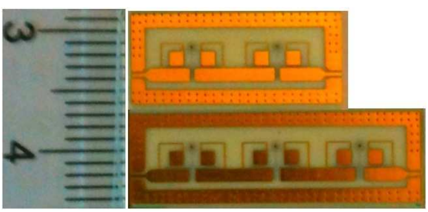
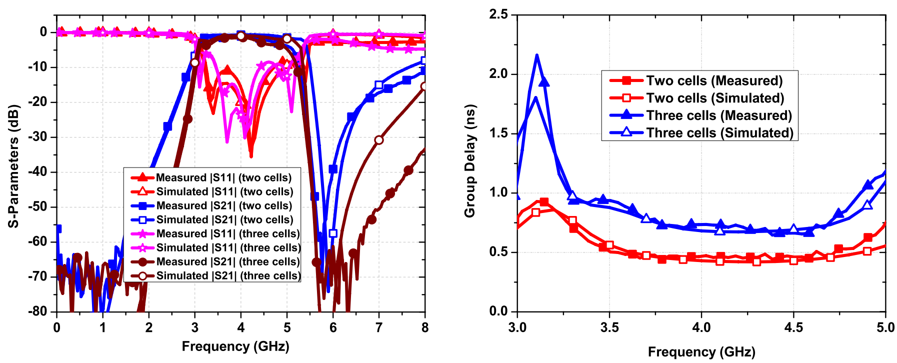


Figure 6. Photograph of the fabricated CRLH UWB bandpass filter with two (top) and three (bottom) unit cells.

co-planar waveguide (CBCPW) structure with width of 0.3 mm and gap of 0.15 mm.

Figure 7(a) shows the simulated and measured characteristics of the UWB filter. In the case of two unit cells, the measured 3-dB bandwidth is 3.09–4.79 GHz, 43.15% refers to the center frequency of 3.95 GHz. The measured in-band insertion loss is approximately 1.1 dB. In the case of three unit cells, the filter has a measured 3-dB fractional bandwidth of 35.51% from 3.22 to 4.61 GHz, and insertion loss of around 1.2 dB.

Figure 7(b) presents the group delay of these two UWB bandpass filters. Both the simulated and measured are flat covering the 3-dB pass band. Table 1 tabulates and summarizes the performances of the proposed filter and other reported ones.



(a) (b)

Figure 7. Simulated (HFSS) and measured characteristics of UWB bandpass filters with two and three unit cells. (a) S parameters and (b) group delay.

Table 1. Performance comparison of UWB bandpass filters.

Reference	[3]	[7]	This Work	
Filter Type	SIR	CRLH	Modified CRLH	
Frequency (GHz)	3.4–4.8	2.465–5.222	3.09–4.79	3.22–4.61
Insertion Loss (dB)	~ 2.8	~ 2	~ 1.1	~ 1.2
Size (mm^3)	$42 \times 42 \times 0.6$	$33 \times 19.8 \times 0.8$	$16.8 \times 8 \times 0.6$	$23.8 \times 8 \times 0.6$
Suppression at 5.8 GHz (dB)	~ 35	~ 15	~ 70	~ 70

4. CONCLUSION

A modified CRLH unit cell is proposed and investigated to achieve high rejection at 5.8 GHz. Based on this unit cell, two UWB bandpass filters are designed and measured. These filters are useful to alleviate the interference between the UWB and WLAN systems.

REFERENCES

1. Zhu, L., S. Sun, and R. Li, *Microwave Bandpass Filters for Wideband Communicatins*, Wiley, NJ, Jun. 2011.
2. Huang, J.-Q., Q.-X. Chu, and C.-Y. Liu, "Compact UWB filter based on surface-coupled structure with dual notched bands," *Progress In Electromagnetics Research*, Vol. 106, 311–319, 2010.
3. Watanabe, K., Z. M. Ma, C. P. Chen, and T. Anada, "An ultra-wideband bandpass filter having sharp skirt property and large attenuations in its stopband," *Microw. Opt. Technol. Lett.*, Vol. 51, No. 9, 2093–2097, Jun. 2010.
4. Lee, C.-H., I.-C. Wang, and L.-Y. Chen, "MMR-based band-notched UWB bandpass filter design," *Journal of Electromagnetic Waves and Applications*, Vol. 22, Nos. 17–18, 2407–2415, 2008.
5. Gao, S. S., X. S. Yang, J. P. Wang, S. Q. Xiao, and B. Z. Wang, "Compact ultra-wideband (UWB) bandpass filter using modified stepped impedance resonator," *Journal of Electromagnetic Waves and Applications*, Vol. 22, No. 4, 514–548, 2008.
6. Caloz, C. and T. Itoh, *Electromagnetic Metamaterials: Transmission Line Theory and Microwave Applications*, Chapter 3, Wiley, NJ, 2006.
7. Lin, X. Q., H. F. Ma, D. Bao, and T. J. Cui, "Design and analysis of super-wide bandpass filters using a novel compact meta-structure," *IEEE Trans. Microw. Theory Tech.*, Vol. 55, No. 4, 747–753, Apr. 2007.
8. Gong, J.-Q. and Q.-X. Chu, "SCRLH TL based UWB bandpass filter with widened upper stopband," *Journal of Electromagnetic Waves and Applications*, Vol. 22, Nos. 14–15, 1985–1992, 2008.
9. Samavati, H., A. Hajimiri, A. R. Shahani, G. N. Nasserbakht, and T. H. Lee, "Fractal capacitors," *IEEE J. Solid-State Circuits*, Vol. 33, No. 12, 2035–2041, Dec. 1998.
10. Monti, G., R. De Paolis, and L. Tarricone, "Design of a 3-state reconfigurable CRLH transmission line based on MEMS switches," *Progress In Electromagnetics Research*, Vol. 95, 283–297, 2009.