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Design of a Compact 5.7–5.9 GHz Filter Based on CRLH Resonator Units

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Abstract—A compact substrate integrated waveguide (SIW) filter based on composite right/left-handed (CRLH) resonator units is implemented in this paper. The filter is composed of two CRLH resonator units serially connected by a SIW transmission line unit. The structure of the filter and equivalent circuit transmission behavior are analyzed, and a novel design method by optimizing the length and width of the interdigital metal slots to decrease the filter operation frequency is proposed. To further demonstrate the design theory and performance of the proposed filter, the filter was designed and fabricated on an RT6010 dielectric material. The measurement results show that the proposed filter works at a center frequency of 5.8 GHz with 200 MHz bandwidth The insertion loss is 2.3 dB, and the filter size is only 10 mm $\times$ 7.4 mm.

1. INTRODUCTION

RF filter is one of the key components for modern wireless communication systems to select the passband signal and reject the stopband signal. Most commercial communication standards are focused on the frequency band that lower than 6 GHz, such as LTE, 5G, Wi-Fi, Bluetooth, and Zigbee. Hence, the design of compact sub-6G filters is a hot research topic for mobile portable devices. Substrate integrated waveguide (SIW) is widely used in RF passive device designs due to low loss, low cost, and flexibility of integration properties, such as filter [1–6], antenna [7–11], phase shifter [12–16], power divider [17–21], and coupler [22–26]. However, SIW filters under 6 GHz is still outsize to meet the requirement of portable communication devices because of the long wavelength. Numerous research works have been presented to reduce size of SIW filters. Due to the advantage of zero order resonance characteristic which makes its resonance frequency relatively irrelevant with device size [27], a CRLH structure is proposed and studied to minimize the size of SIW passive devices [28–33]. A typical rectangular CRLH filter is reported in [30] with compact size, and the operation frequency is 6.8 GHz with 3 dB insertion loss, which is still out of 6 GHz frequency limitation. In this work, a novel design method is proposed to further realize a compact CRLH filter working inside 6 GHz frequency range. The structure and equivalent circuit are analyzed to discuss the frequency limitation of the filter. The coupling capacitor of the filter is then designed and optimized to reduce resonate frequency. A 5.8 GHz RF filter with 200 MHz bandwidth is finally implemented for sub-6G wireless systems with a size of only 10 mm $\times$ 7.4 mm, and the insertion loss is low as 2.3 dB.

2. FILTER STRUCTURE AND ANALYSIS

The designed SIW filter based on CRLH resonator units is shown in Fig. 1(a). Two CRLH resonators composed of interdigital rectangular-shaped metal slots are coupled with a SIW transmission line (SIW

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TL). Metallization through holes are placed as vias to connect CRLH units to backside ground. The SIW TL is adopted to restrict the propagating waves by arrays of vias which results in low loss for the filter. The CRLH units can demonstrate resonators which are independent of their physical lengths, and hence they can be more compact, especially at lower frequencies.

The equivalent circuit of single CRLH resonator unit is shown in Fig. 1(b). The filter circuit is composed of a left-hand series capacitor C_L, a shunt inductor L_L, a right-hand shunt capacitor C_R, and a series inductor L_R. Capacitor C_L is the coupling capacitor between the interdigital fingers of the CRLH units, and C_R is the coupling capacitor from the finger slots to the ground. Inductor L_L is introduced by the self-inductance of the vias in the structure, and L_R is generated by the inductance of the rectangular slots in the CRLH units. The "left-hand" property is under s certain frequency range when electromagnetic wave passes through the structure, and the effective dielectric constant and effective permeability are negative. On the other hand, the "right hand" property is under another frequency range, and the effective dielectric constant and effective permeability are positive. Therefore, complex resonance behavior of this structure can be accomplished to improve the performance of RF passive devices.

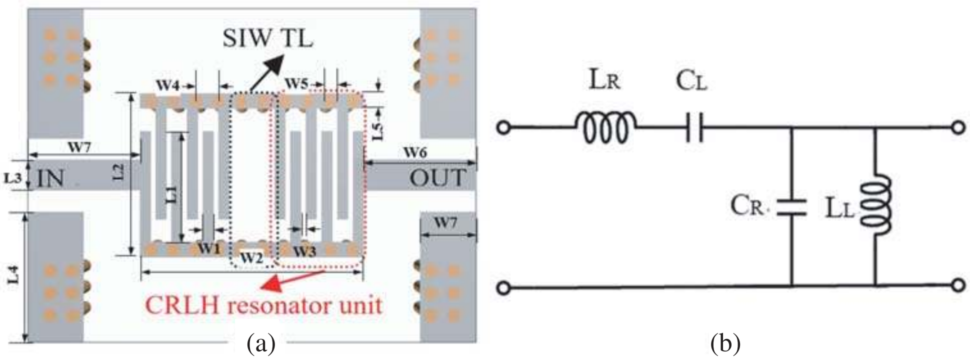

Figure 1. (a) Conventional SIW filter with interdigital rectangular CRLH units, (b) equivalent circuit of single CRLH resonator unit.

The proposed filter is composed of two CRLH resonator units which are connected with the SIW TL. The overall equivalent circuit of the filter is illustrated in Fig. 2. In the equivalent circuit, R_1, R_2, and R_3 are the series and shunt resistances of the lossy material. C_1 and C_2 are generated by the right-handed capacitances (C_R) of two CRLH units, while C_3 is generated by the left-handed capacitance (C_L) of two CRLH units. Consequently, C_1 and C_2 are determined by the area of rectangular plates of CRLH units, and C_3 is determined by the length of interdigital slots of CRLH units.

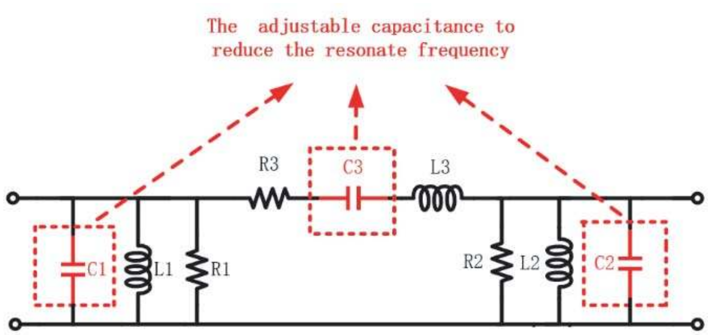

Figure 2. The equivalent circuit of the filter.

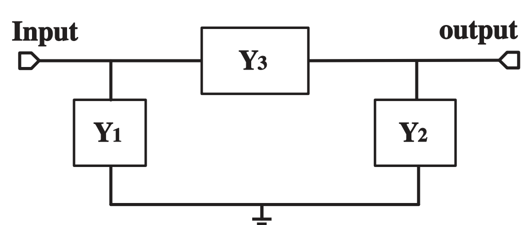

Figure 3. Simplified Y model of the filter.

A simplified equivalent Y model is illustrated in Fig. 3 to calculate the transmission behavior of the filter.

The values of R_1, R_2, and R_3 are normally very small which mainly affect the insertion loss, while showing little effect on the resonate frequency, hence these resistances can be neglected in the equivalent circuit. It can be derived from the equivalent circuit in Fig. 2 and Fig. 3:

$$Y_1 = \frac{1 - \omega^2 L_1 C_1}{j\omega L_1} \tag{1}$$

$$Y_2 = \frac{1 - \omega^2 L_2 C_2}{j\omega L_2} \tag{2}$$

$$Y_3 = \frac{j\omega C_3}{1 - \omega^2 L_3 C_3} \tag{3}$$

A Y matrix equation can be derived based on the Y model in Fig. 3.

$$Y = \begin{bmatrix} Y_{11} & Y_{21} \\ Y_{12} & Y_{22} \end{bmatrix} = \begin{bmatrix} Y_1 + Y_3 & -Y_3 \\ -Y_3 & Y_2 + Y_3 \end{bmatrix} \tag{4}$$

Putting Equations (1)–(3) to the matrix in Equation (4), then

$$Y_{11} = \frac{1 - \omega^2 L_1 C_1 - \omega^2 L_3 C_3 - \omega^2 L_1 C_3 + \omega^4 L_1 C_1 L_3 C_3}{j\omega L_1 (1 - \omega^2 L_3 C_3)} \tag{5}$$

$$Y_{22} = \frac{1 - \omega^2 L_2 C_2 - \omega^2 L_3 C_3 - \omega^2 L_2 C_3 + \omega^4 L_2 C_2 L_3 C_3}{j\omega L_2 (1 - \omega^2 L_3 C_3)} \tag{6}$$

$$Y_{21} = Y_{12} = -\frac{j\omega L_3}{1 - \omega^2 L_3 C_3} \tag{7}$$

When the value of Y_{21} is infinite, or Y_{11}/Y_{22} equals zero, the circuit will generate resonation. In Equations (5)–(7), the capacitance is normally at pF level, the inductance normally at nH level, and the frequency at GHz level. Consequently, the product term $\omega^4 L_1 C_1 L_3 C_3$ and $\omega^4 L_2 C_2 L_3 C_3$ in above equations can be neglected. Therefore, three resonant frequencies can be derived:

$$f_{O1} = \frac{1}{2\pi\sqrt{L_3 C_3}} \tag{8}$$

$$f_{O2} = \frac{1}{2\pi\sqrt{L_1 C_1 + L_3 C_3 + L_1 C_3}} \tag{9}$$

$$f_{O3} = \frac{1}{2\pi\sqrt{L_2 C_2 + L_3 C_3 + L_2 C_3}} \tag{10}$$

It is illustrated in Equations (8)–(10) that three resonant frequencies are generated by this CRLH structure, and the value of the resonant frequency is dominated by capacitances and inductances. The inductances are obtained solely by the metallic vias between the plates, which are fixed in the design. Consequently, the capacitances provided by interdigital capacitance and ground-coupling capacitance become the only alterable elements. Therefore, a novel design method is proposed in this work by optimizing length L_1 to increase C_3 and width W_1 to increase C_1 and C_2, which will be discussed in details in the following section.

If the SIW TL section (as shown in Fig. 1(a)) is taken into account, then the total phase shift of the CRLH filter on achieving a zeroth order mode can be written as [30]:

$$\beta l = 2\phi_C + \phi_{SIW} = 0 \tag{11}$$

where ϕ_C is the phase shift due to two CRLH units, and ϕ_{SIW} is the phase shift due to the SIW section:

$$\phi_C = \omega\sqrt{L_R C_R} - \frac{1}{\omega\sqrt{L_L C_L}} \tag{12}$$

$$\phi_{SIW} = \frac{2\pi}{\lambda_g} = \frac{2\pi}{\lambda_0}\sqrt{1 - \left(\frac{\lambda_0}{2a_{eff}}\right)^2} \tag{13}$$

where a_{eff} is the effective width of the SIW TL, then a resonant frequency can be derived by putting Equations (12) and (13) to Equation (11) and solving the equation:

$$\omega = \frac{\frac{\pi}{\lambda_0}\sqrt{1-\left(\frac{\lambda_0}{2a_{eff}}\right)^2} + \sqrt{\left(\frac{\pi}{\lambda_0}\right)^2\left[1-\left(\frac{\lambda_0}{2a_{eff}}\right)^2\right] + 4\frac{\sqrt{L_R C_R}}{\sqrt{L_L C_L}}}}{2\sqrt{L_R C_R}} \tag{14}$$

It is shown in Equation (14) that the SIW TL section gives us more freedom to tune the operation frequency of the CRLH filter by optimizing the effective width of the SIW TL section (a_{eff}). Consequently, the CRLH filter with SIW TL section shows the potential to achieve a compact size.

3. FILTER DESIGN

Based on above analysis, the resonant frequencies of the filter are determined by the series interdigital capacitance C_3 and the shunt ground-coupling capacitance C_1/C_2. The value of C_3 depends on the length of the interdigital metal slots (L_1), and the value of C_1/C_2 depends on the width of the interdigital metal slots (W_1).

An AWR design environment software is used to simulate this filter. The equivalent circuit elements can be derived by generating a special model, which is achieved by simulating the frequency response of the filter using the AWR software. In this work, the value of C_3 varying with different length L_1 is simulated while keeping other dimension parameters constant, which is shown in Fig. 4. It is illustrated that the average value of C_3 is only 3.5 pF when $L_1 = 2$ mm. The value increases to 12 pF when $L_1 = 5$ mm, and the resonant frequencies are then decreased according to Equations (8)–(10). For the trade-off among resonant frequency, filter size, insertion loss, and matching performance, the final value of length L_1 is chosen as 4 mm.

The values of C_1/C_2 varying with different lengths W_1 are also simulated while keeping other dimension parameters constant, shown in Fig. 5. The curves of C_1 and C_2 coincide with each other in Fig. 5 due to the same value of C_1 and C_2 as a result of the symmetrical structure. It is illustrated that the average value of C_1/C_2 is only 1.2 pF when $L_1 = 0.2$ mm. The value increases to 4.9 pF when $W_1 = 0.8$ mm, and the resonant frequencies are then decreased according to Equations (9)–(10). For the trade-off among resonant frequency, filter size, insertion loss, and matching performance, the final value of width W_1 is chosen as 0.6 mm.

The bandwidth of the filter can be realized by tuning the equivalent inductance and capacitance values of the structure. The two CLRH units as shown in Fig. 1 are usually symmetrical, so L_1 is the

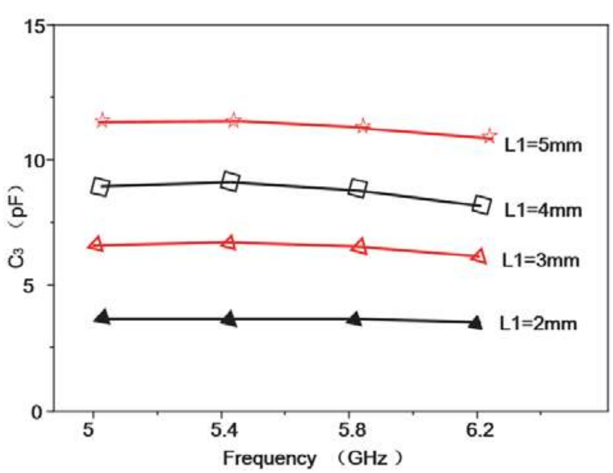

Figure 4. Capacitance C_3 varies with the length L_1.

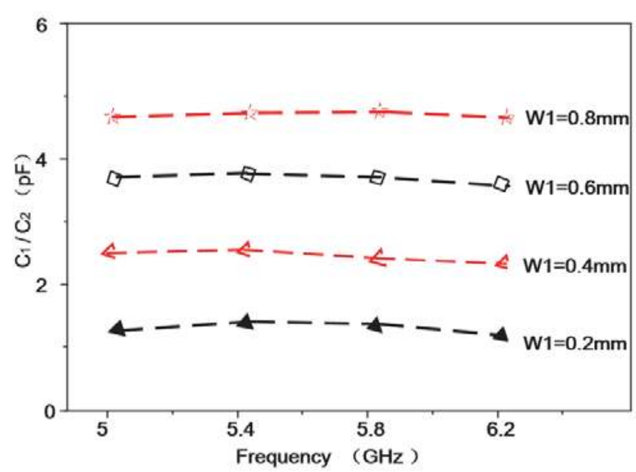

Figure 5. Capacitance C_1/C_2 varies with the width W_1.

same as L_2, and C_1 is the same as C_2. Therefore, the resonant frequency f_{o2} equals f_{o3} in Equations (9)–(10). It can be easily observed in Equations (8)–(10) that the resonant frequency f_{o1} is higher than f_{o2} or f_{o3}. The equivalent elements L_3, C_3 can be firstly optimized to set f_{o1} as 5.9 GHz. Then L_1, C_1, L_2, C_2 can be further tuned to set f_{o2}/f_{o3} as 5.7 GHz. Consequently, 200 MHz bandwidth is finally realized.

For the design of the proposed filter, the insertion loss, stopband rejection, and matching properties are also considered as critical design factors to tune the filter parameters except resonant frequency. The final physical parameters after optimization are shown in Table 1. A compact SIW filter is then finally designed and optimized. The simulated S parameters are shown in Fig. 6. The center resonant frequency is 5.9 GHz with 200 MHz bandwidth. This center frequency is 100 MHz higher than the 5.8 GHz design goal, since the measured center frequency will normally decrease to the lower frequency after fabrication. The insertion loss is only 1.93 dB. Consequently, a compact filter with low resonant frequency and low loss is successfully designed based on the optimization method proposed in this work. With these properties, the proposed filter shows the potential ability to be used in sub-6G wireless communication systems.

Table 1. Dimensions of the proposed filter.

Dimension	Value (mm)	Dimension	Value (mm)
W_1	0.6	L_1	4
W_2	10	L_2	7.4
W_3	0.2	L_3	1.1
W_4	1	L_4	5.8
W_5	0.5	L_5	0.7
W_6	5	W_7	4.6

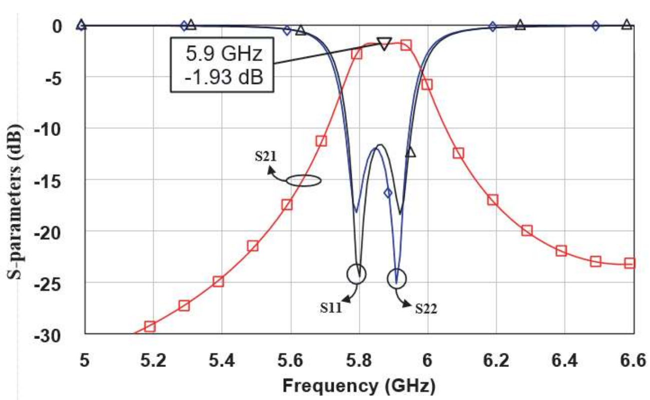

Figure 6. Simulated S parameters of the filter.

4. IMPLEMENT AND MEASUREMENT

To further demonstrate the merit, a SIW filter based on the proposed interdigital CRLH units is implemented with RT6010 material of which dielectric constant is 10.2, as shown in Fig. 7. The core filter size is only 10 mm × 7.4 mm.

The input and output signals are fed in and out through the RF SMA connectors. The S parameters measurement results are shown in Fig. 8. It shows that the working frequency band of this proposed filter ranges from 5.7 GHz to 5.9 GHz, and the insertion loss S_{21} is only 2.3 dB. The measured group delay of the proposed filter is shown in Fig. 9. The maximum passband group delay is located at

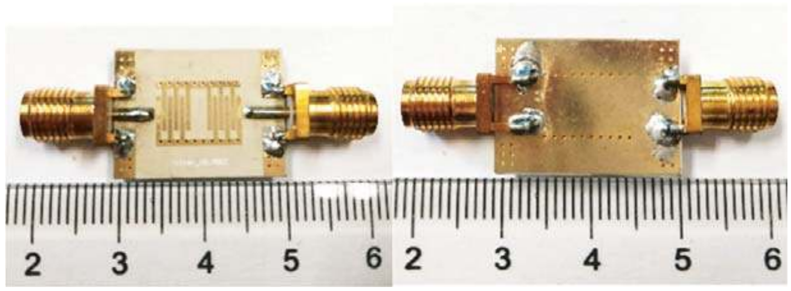

Figure 7. Photo of the filter, (a) topside, (b) backside.

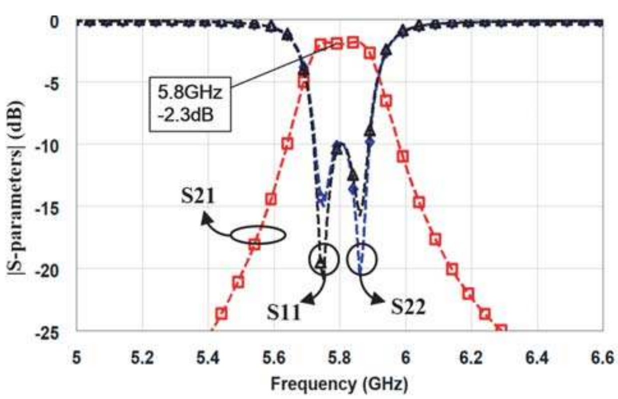

Figure 8. Measured S parameters of the filter.

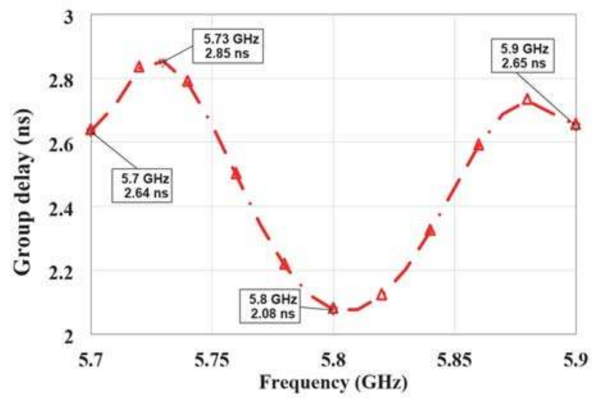

Figure 9. Measured group delay of the filter.

5.73 GHz, which is 2.85 ns. The minimum passband group delay is 2.08 ns at 5.8 GHz. Therefore, the group delay variation during the whole passband is only 0.77 ns, which is low for this 200 MHz compact filter. Hence, a novel compact CRLH SIW filter is successfully designed and implemented for sub-6G applications. The measurement results demonstrate that the designed method proposed in this work can effectively decrease the operation frequency of a CRLH filter to meet the requirement of sub-6G applications, while maintaining compact size, low loss, and low group delay properties of the filter.

Many studies have been focused on improving the performance of the compact CRLH filter in recent years. The performances of several reported CRLH filters are summarized and compared in Table 2. The physical sizes of the reported filters are normalized by the wavelength of the center frequency (λ_0). The operation frequency of the filter, reported in [29], can be as low as 3 GHz, with a good bandwidth. However, the size of this filter is too large ($0.8\lambda_0 \times 0.5\lambda_0$). In [30, 31], two relatively compact filters using

Table 2. Comparison of CRLH filters.

Ref.	Center frequency (GHz)	Insertion loss (dB)	Bandwidth (MHz)	Size ($\lambda_0 \times \lambda_0$)
[29]	3/6/9	3	150/500/300	0.8×0.5
[30]	6.8	3	200	0.23×0.14
[31]	7.3	2.2	50	0.40×0.32
[32]	5.3	2.7	500	0.51×0.13
[33]	5	2.7	700	0.37×0.25
This work	5.8	2.3	200	0.19×0.14

CRLH units are reported. However, their center operation frequencies are beyond the 6 GHz limitation. Two CRLH filters, presented in [32, 33], are well designed for sub-6G applications. However, their sizes are still large to meet the requirement of portable devices. For the design proposed in this work, the filter size is only $0.19\lambda_0 \times 0.14\lambda_0$, and the center frequency is only 5.8 GHz. It is demonstrated that the proposed filter can be considered as one of the most compact CRLH filters with a low passband loss and high stopband rejection for sub-6G systems.

5. CONCLUSION

A novel SIW filter with CRLH resonator units is designed for sub-6G communication systems. The structures of the resonator units and filter are discussed. The key factors to limit the resonant frequencies are calculated and analyzed. A novel design method is proposed by optimizing length L_1 to increase interdigital capacitance C_3 and width W_1 to increase ground-coupling capacitance C_1 and C_2. The proposed filter is finally designed, fabricated, and tested, and a 5.7 GHz $\sim$ 5.9 GHz compact filter with only 2.3 dB insertion loss and 0.77 ns group delay variation is successfully realized for sub-6G portable devices.

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