

# High Pass Filter Design Using Folded Coplanar Waveguide CRLH Transmission Line

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## ABSTRACT

*A novel unit cell for a high pass filter was designed based on a composite right/left-handed structure that uses a folded coplanar waveguide. The equivalent circuit model for the unit cell was extracted from the geometry of the unit cell, and the effect of each main parameter of the unit cell was analyzed. The equations to calculate the immittance values of the equivalent circuit elements were formulated, and moreover, the dispersion characteristics and energy the distributions of the electromagnetic fields were simulated to determine the characteristics of the composite right/left-handed structure. Finally, the high pass filters were implemented as a series of the proposed unit cells. We show that the experimental results were in good agreement with those obtained from the simulation. Thus, the high pass filter was found to achieve a baseband insertion loss of 3 dB and a stopband attenuation of 70 dB.*

**Key words:** Composite Right/Left-Handed (CRLH), Folded Coplanar Waveguide, High Pass Filter, Unit Cell.

## 1. INTRODUCTION

In communication systems, filters have been widely used for selecting the desired frequency from multiple input signals. For the development of the systems or the instruments, filters are required to have compact sizes and low loss, as well as the ability of low-power operation. In order to achieve these requirements, special structures or materials should be taken in filter design. Over the last decade, left-handed material (LHM) has received much attention since it has simultaneously negative values of permittivity  $\epsilon$  and permeability  $\mu$  [1] and demonstrated successfully in 2000 [2]. After that, a transmission line approach of LHM was introduced in 2002 [3]-[4]. The LH transmission line is widely used because of its advantages, such as high frequency selectivity, low loss and wide bandwidth. It can be practiced in planar configurations and compatible with modern microwave integrated circuits (MICs) [5]. However, the LH transmission line always has a spurious right-handed (RH) range because the transmission line gets typically an inherent series inductance and shunt capacitance. So a purely left-handed (PLH) transmission line does not exist in fact and the transmission line, which has both a LH range and a RH range, is called a composite right and

left-handed (CRLH) transmission line (TL) [6]-[8]. An effectively homogeneous CRLH TL can be constructed by cascading LC-based unit cells. The LC-based unit cell for a CRLH transmission line consists of the impedance constituted by a RH inductance with a LH capacitance in series components and the admittance constituted by a RH capacitance with a LH inductance in parallel components.

In the respect of designing filters by MICs or monolithic microwave integrated circuits (MMICs), coplanar waveguide (CPW) is more suitable than conventional microstrip lines since the fabrication of CPW is simple and crosstalk effects between the adjacent lines are weak [9]-[10].

In this paper, to design a high pass filter with a compact size and a steep skirt performance, the unit cell with high pass property is proposed on the folded CPW transmission line with a CRLH structure. To analyze the performance of the unit cell, the equivalent circuit of the unit cell is introduced and the immittance elements of the equivalent circuit are formulated. And then the dispersion characteristics and electromagnetic energy distributions over the CRLH structure are simulated. Finally, a high pass filter is fabricated by cascading the proposed unit cells in series arrangements and S-parameter characteristics of the filter are measured by a vector network analyzer (Agilent N5230A). And the measurement results are compared with the simulation results.

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## 2. UNIT CELL CONSTRUCTED ON FCPW TL

The unit cell based on CRLH using folded coplanar waveguide transmission line (FCPW TL) is shown in Fig. 1 [11]. A FCPW TL is a kind of CPW, which consists of a dielectric substrate and two conductors placed on both sides of the substrate. And each conductor is structured as a conventional CPW on both bottom and top layer, with a signal line between two ground planes separated by a narrow gap. In order to build a CRLH structure on the FCPW TL, the signal lines on both top and bottom layer are reformed as shown in Fig. 1. The center section of the signal line on the top layer has been cut off. On the other hand, the end sections of the signal line on the bottom layer are removed and the rest of the line is connected at the one of ground planes on the same layer. Therefore, the input signal is entered in the signal line on the top layer only, and transmitted into the signal line on the bottom layer due to the electrical reactance components between two signal lines.

As the physical geometry of unit cell adds an additional parallel capacitance and serial reactance component ( $C_L, L_L$ ) to the distributed element components ( $R_S, L_R, G_S, C_R$ ) of the transmission line, it can be modeled as the circuits combined a series RLC resonant circuit ( $R_S, L_R, C_L$ ) and a shunt GLC parallel resonant circuit ( $G_S, L_L, C_R$ ). Therefore, the equivalent circuit for the proposed unit cell can be represented as shown in Fig. 2. The distributed element components ( $R_S, L_R, G_S, C_R$ ) are distributed in a folded CPW transmission line. In a LH components, the series capacitance  $C_L$  is distributed in the overlapped area between the signal line on the top layer and the signal line on the bottom layer, which is in proportion to the relative area. Moreover, the parallel inductance  $L_L$  depends on the narrow strip line in which connects the signal line with the shorted ground plane on the bottom layer.

According to analysis on the unit cell structure, the values of the equivalent capacitances ( $C_L$  and  $C_R$ ) and the equivalent inductance ( $L_L$ ) can be expressed as

$$R_S = \sqrt{\frac{2\omega\mu_0}{\sigma_c}} \frac{2L+D}{W-2S} \quad (1)$$

$$G_S = \sigma_d \frac{(W-2S)(2L+D)}{H} \quad (2)$$

$$C_R = \sqrt{C_{oe} C_{oe}^a} (2L+D) \quad (3)$$

$$L_R = Z_{01}^2 \sqrt{C_{oe} C_{oe}^a} (2L+D) \quad (4)$$

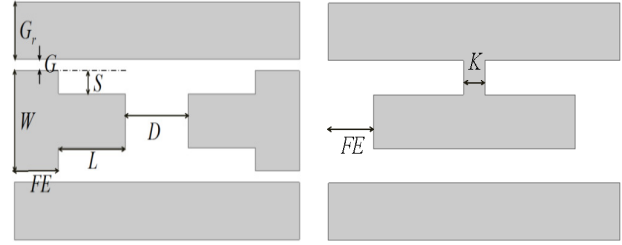
$$C_L = \epsilon_0 \epsilon_{eff} \frac{(W-2S)L}{H} \quad (5)$$

$$L_L = Z_{02} (S+G) \frac{\sqrt{\epsilon_{eff}}}{c} \quad (6)$$

$$Z_{01} = \frac{1}{c\sqrt{C_{oe} C_{oe}^a}} \quad (7)$$

$$Z_{02} = \frac{1}{c\sqrt{C_{oe}' C_{oe}^a}} \quad (8)$$

where  $S, L, D, FE$  and  $K$  are the design parameters of the unit cell.  $\epsilon_0, \mu_0$  and  $c$  are the permittivity, permeability and light velocity of free space, respectively. And  $\sigma_c$  and  $\sigma_d$  are the conductivities of signal line and dielectric substrate in a FCPW TL.  $H$  is the thickness of dielectric substrate in a FCPW TL.



(a) Top view (b) Bottom view

Fig. 1. Physical geometry of the unit cell

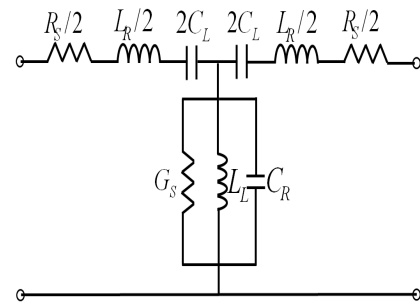


Fig. 2. Equivalent circuit model for the unit cell

The capacitances  $C_{oe}$  and  $C_{oe}'$  are the capacitive components on the top and the bottom transmission line, respectively.  $C_{oe}^a$  is the capacitance when replacing the dielectric materials by air. The characteristic impedance  $Z_{01}$ ,  $Z_{02}$  and the effective dielectric constant  $\epsilon_{eff}$  are calculated by the equations in [12].

Consequently, the equivalent impedance  $Z$ , admittance  $Y$ , the series resonant frequency  $\omega_{se}$  and the shunt resonant frequency  $\omega_{sh}$  can be formulated as follows:

$$Z = R_S - j \frac{1}{\omega C_L} \left[ 1 - \left( \frac{\omega}{\omega_{se}} \right)^2 \right] \quad (9)$$

$$Y = \frac{G_S \left[ 1 - \left( \frac{\omega}{\omega_{sh}} \right)^2 \right] + j\omega C_R}{1 - \left( \frac{\omega}{\omega_{sh}} \right)^2} \quad (10)$$

$$\omega_{se} = \frac{1}{\sqrt{L_R C_L}}, \quad \omega_{sh} = \frac{1}{\sqrt{L_L C_R}} \quad (11)$$

And the propagation constant, attenuation constant and phase constant of the equivalent circuit model can be calculated from the transmission parameter of  $S_{21}$ .

$$\begin{aligned} \gamma &= \alpha + j\beta = \sqrt{ZY} \\ &= -\frac{1}{l} \left[ \ln(|S_{21}|) + j\phi(S_{21}) \right] \end{aligned} \quad (12)$$

The dispersion characteristics of  $\beta$  generally appears a continuous function of frequency as a curve varying within  $|\beta| \leq \pi$ . And  $l$  and  $\varphi(S_{21})$  represent the physical length  $(2L+D)$  of the unit cell in a specific implementation and the phase of  $S_{21}$ , respectively.

### 3. SIMULATION RESULTS

The unit cell is implemented on the FCPW TL with the relative dielectric constant  $\epsilon_r$  of 2.5 and tangent loss of 0.001. The thickness  $H$  of the dielectric substrate is 0.787 mm and the thickness  $T_c$  of the conductor sheet is 35  $\mu$ m. The values of the signal feeder line width  $W$  and the gap width  $G$  between the feeder line and the ground plane can be calculated by the commercial simulation tool (ADS Linecalc), corresponding to 50  $\Omega$  characteristic impedance of a CPW structure. Moreover, the input and output ports of the unit cell are set to 50  $\Omega$  characteristic impedance in FCPW configuration, which results in the feed line width  $W = 8.74$  mm and the gap width  $G = 0.3$  mm.

To analyze the behaviors among the design parameters, three dominant sets of the parameters  $L$ ,  $D$  and  $S$  are evaluated. In the process of the simulation, while the one of the parameters is calculated, the other parameters are fixed on the constant values.

From the simulation results, the resonant frequencies decrease because of the increments of the immittance components ( $C_R$ ,  $L_R$ ,  $C_L$ ,  $L_L$ ) according as  $L$  and  $D$  increase. Those are different values, so that there are two resonant frequencies which are represented by a LH resonant frequency and a RH resonant frequency. Particularly, when the length of  $L$  is close to the guided wavelength of  $\lambda/16$  (6.4 mm), two resonant frequencies get closer and the stopband frequency range is very well specified on the graphs in Fig. 3(a) and (b).

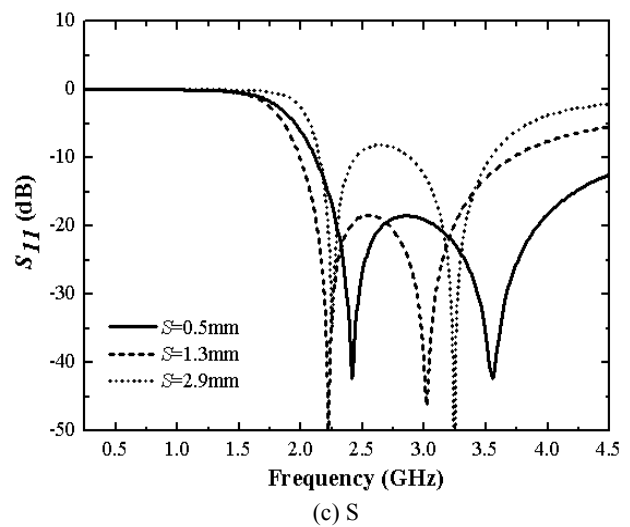
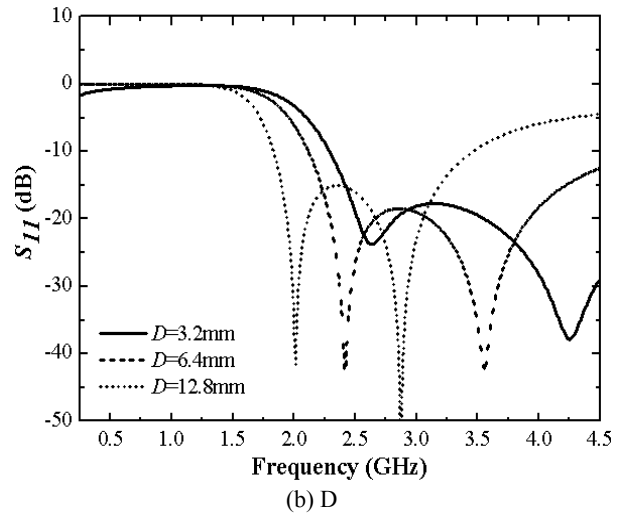
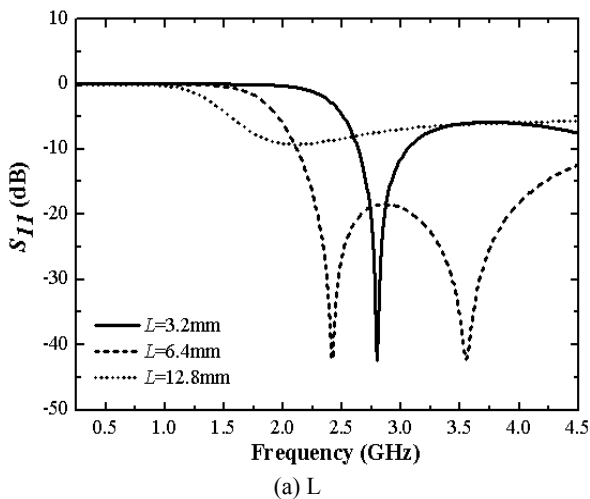


Fig. 3.  $S_{21}$  (dB) characteristics as a function of geometrical parameters

In addition, when the length of  $S$  is shorter than  $\lambda/64$  (1.3 mm), the resonant frequencies decrease as shown in the Fig. 3(c). It is reason that the resonant frequencies increase since the augmented effects of the inherent capacitances  $C_{oe}$  and  $C_{oe}$  increase the component  $C_R$  and  $C_L$ . Therefore, the capacitances primarily depend on the widths and lengths of the signal lines. The optimal widths and lengths of the design parameters are shown in Table 1. Also, in case of a low loss FCPW TL, the equivalent immittance components calculated by the equations (1) to (6) are  $R_S = 1.08 \Omega$ ,  $G_S = 0.001 S$ ,  $C_R = 0.54 pF$ ,  $C_L = 0.85 pF$ ,  $L_R = 3.48 nH$ ,  $L_L = 2.24 nH$ , respectively.

Table 1. Physical dimensions of the proposed unit cell (Unit: mm)

Parameters	L	K	D	$G_r$	FE	S	G	W
Values	6.35	2	6	5	4.2	0.5	0.3	8.74

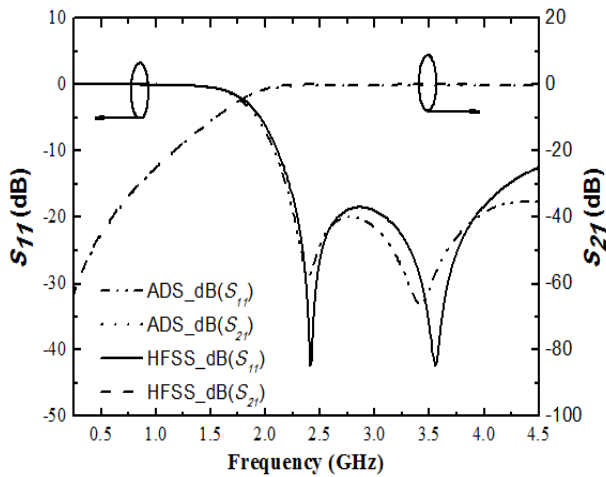


Fig. 4. S-parameter simulation results of the unit cell

The S-parameter characteristics are shown in Fig. 4 as comparing the simulation results of the proposed unit cell done by ADS and HFSS, which has high pass property. The magnitude curves of  $S_{11}$  in the passband and the magnitude curves of  $S_{21}$  in the stopband are excellent agreements with good performances. In the passband, the  $S_{11}$  ripples are below -15 dB, and at the same time the magnitude curves of  $S_{21}$  get maximal flatness. Also, the cutoff frequency is 1.75 GHz, and the length of L, space of S and distance of D are  $\lambda/16$ ,  $\lambda/128$  and  $\lambda/8$ , respectively. Compared with conventional filters, which stubs are  $\lambda/8$  [13] or  $\lambda/4$  [14] in general, this is more advantageous to achieve small size in filter design.

To confirm a CRLH structure, the dispersion diagram is considered as shown in Fig. 5. The results are simulated with the physical dimensions in Table 1 by ADS and HFSS. And the LH mode occurs in the frequency range lower than 2.66 GHz and the RH mode occurs in the frequency range higher than 2.66 GHz. It means that the propagating waves have backward and forward directions simultaneously. As a result, the proposed unit cell provides the CRLH characteristics.

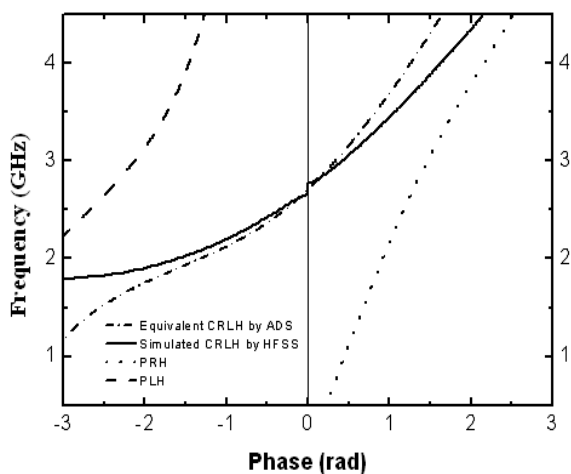
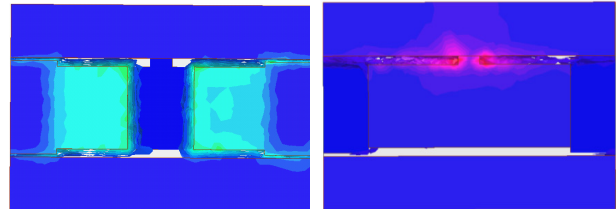


Fig. 5. Dispersion diagram of the unit cell

In addition, energy distributions of the electromagnetic fields are depicted as shown in Fig. 6. When input signal enters into the unit cell, the energy is accumulated inside the overlapping

area between the signal lines on the top and the bottom layer, which is electric energy in Fig. 6(a). Because of the electromagnetic interaction, the electric energy turns to be the magnetic energy as time elapses. The magnetic energy distribution, corresponding to the accumulated energy distribution around the narrow line which connects the signal line to the ground plane on the bottom layer, is shown in Fig. 6(b). This process is done repeatedly while the signal energy is transmitted from the input to the output port.

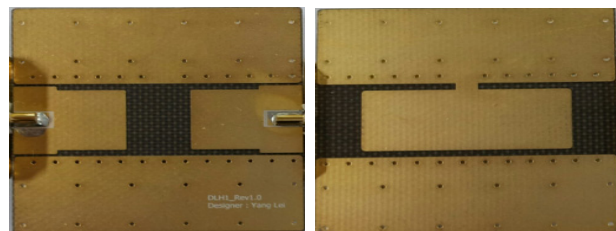


(a) Electric energy (b) Magnetic energy

Fig. 6. Energy distributions of unit cell

#### 4. MEASUREMENT RESULTS OF UNIT CELL AND HIGH PASS FILTER

The proposed unit cell is fabricated in the dimensions as shown in Table 1. The fabricated unit cell in Fig. 7 is measured by vector network analyzer (N5230A). The comparison between the simulation and measurement results are shown in Fig. 8. The shapes of the S-parameter curves are similar, but there is a slightly mismatch between the cutoff frequencies. The measured cutoff frequency is shifted to high frequency band and it is considered that the implementation of ground plane is not enough to play a role of perfect ground plane. Therefore, the electrical energy, which is accumulated inside the overlapped area between the signal lines, is less than the desired simulation amount. Even so, the unit cell still can be used in designing the high pass filter since the  $S_{11}$  ripples in the passband get a regulation and it is favorable to get a wide passband. From these properties, the high pass filter is implemented by cascading three unit cells in series and the layout patterns are shown in Fig. 9. Also, the optimal dimensions of the high pass filter are listed in Table 2.



(a) Top view (b) Bottom view

Fig. 7. Fabricated geometry of the unit cell high pass filter

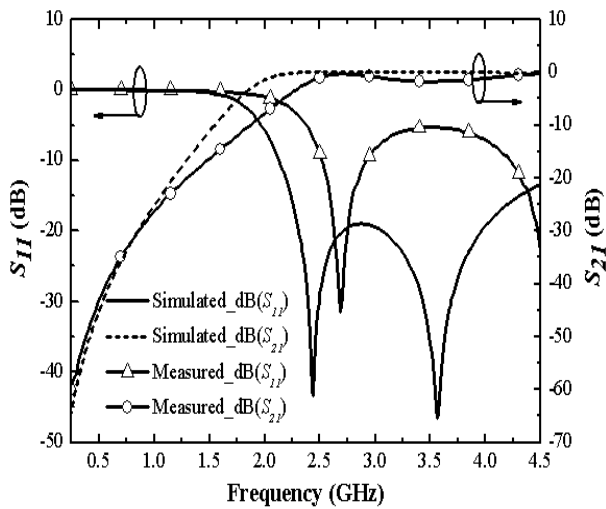


Fig. 8. S-parameter simulation and measurement results of the unit cell

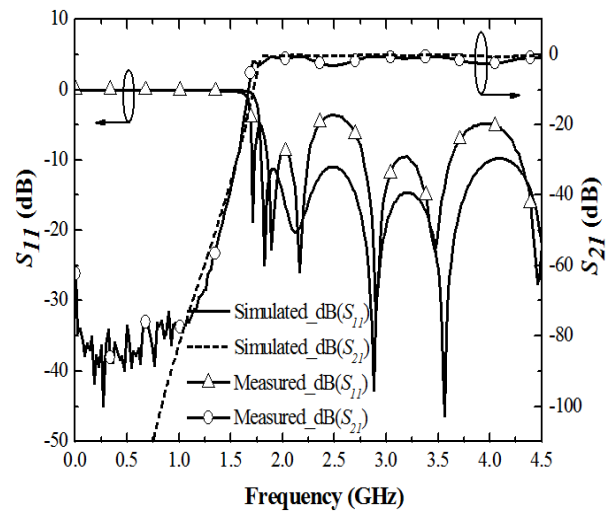


Fig. 10. Simulation and measurement results of proposed high pass filters (22.2mm × 90.5mm)

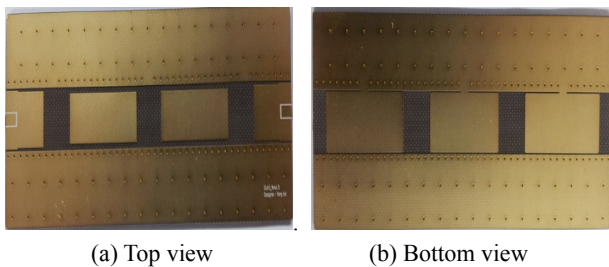


Fig. 9. Fabricated physical geometry of the three-cell high pass filter

Table 2. Physical dimensions of the proposed high pass filter(Unit:mm)

Parameters	$L_1$	$L_2$	Gr	FE	$S_1$	$S_2$	D
Values	8.05	21	6.4	4.1	0.2	0.6	8.2
Parameters	$D_1$	$D_2$	W	G	K	H	$T_c$
Values	8.05	7.75	8.74	0.3	2.3	0.787	35

The simulation and measurement results of the proposed high pass filter are shown in Fig. 10. The S-parameter curves have similar shapes, but the cutoff frequencies and passband ripples are partially a little mismatched because of the lack of the production techniques and insufficient ground effects. The measured cutoff frequency of the three-cell high pass filter is 1.76 GHz, which is very close to the target cutoff frequency of 1.75 GHz. The attenuation of the filter is below 70 dB in the stopband, and the skirt effect is much better than that of the unit cell high pass filter. Also, the insertion loss is less than 3 dB in the passband. Even though the S-parameter characteristics of the fabricated filter do not completely same as those of the target filter, the measurement results are agreed well with the simulation.

### 5. CONCLUSIONS

The unit cell with high pass property has been proposed on the folded coplanar waveguide with a CRLH structure. Also, the equivalent circuit components have been extracted from the geometry of the unit cell and the parameters have been investigated to design the high pass filter. Moreover, the S-parameter characteristics of the equivalent circuit model and the unit cell have been simulated and compared. Finally, we applied a good high pass property of the proposed unit cell to design the three-cell high pass filter with a steep skirt effect and good suppression performance. The attenuation in the stopband and the insertion loss in the passband have been evaluated in 70 dB and 3 dB, respectively. Even if the measurement results of the fabricated filter do not perfectly same as those of the desired filter, this implementation scheme can be usefully used in designing the high pass filter.

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### REFERENCES

- [1] V. Veselago, "The electrodynamics of substances with simultaneously negative values of  $\epsilon$  and  $\mu$ ," Soviet Physics Uspekhi, vol. 10, no. 4, Feb. 1968, pp. 509-514.
- [2] D. R. Smith, W. J. Padilla, D. C. Vier, S. C. Nemat-Nasser, and S. Schultz, "Composite medium with simultaneously negative permeability and permittivity," Physics Review Letter, vol. 84, no. 18, May. 2000, pp. 4184-4187.
- [3] C. Caloz and T. Itoh, "Application of the transmission line theory of left-handed (LH) materials to the realization of a microstrip LH transmission line," Proc. IEEE-AP-S

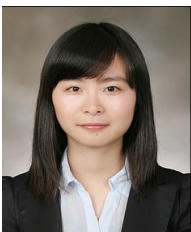
USNC/URSI National Radio Science Meeting, vol. 2, Jun. 2002, pp. 412-415.

- [4] A. A. Oliner, "A planar negative-refractive-index medium without resonant elements," Proc. IEEE MTT-S International Symposium, vol. 1, 2003, pp. 191-194.
- [5] C. Caloz and T. Itoh, *Electromagnetic metamaterials: transmission line theory and microwave applications*, John Wiley & Sons, Inc., 2006, pp. 15, 83-84.
- [6] C. Caloz and T. Itoh, "Novel microwave devices and structures based on the transmission line approach of meta-materials," Proc. IEEE MTT-S International Symposium, vol. 1, Jun. 2003, pp. 195-198.
- [7] A. Lai, T. Itoh, and C. Caloz, "Composite right/left-handed transmission line metamaterials," IEEE Microwave Magazine, Sep. 2004, pp. 34-50.
- [8] Q. Zhu and S. J. Xu, "Composite right/left handed transmission line metamaterials and applications," Proc. Meta. 2008 International workshop, Nov. 2008, pp. 72-75.
- [9] R. N. Simons, *Coplanar waveguide circuits, components, and systems*, John Wiley & Sons, Inc., 2001, p. 1, pp. 87-109.
- [10] P. Wen, "Coplanar waveguide: a surface strip transmission line suitable for nonreciprocal gyromagnetic device applications," IEEE Transaction on Microwave Theory and Techniques, vol. 17, no. 12, Dec. 1969, pp. 1087-1090.
- [11] L. Yang, S. D. Seo, H. R. Cho, and D. Y. Yang, "Analysis of unit cells for high pass filter using left-handed transmission line," Proc. APCC2012, Oct. 2012, pp. 29-33.
- [12] S. S. Bedair and I. Wolff, "Fast and accurate analytic formulas for calculating the parameters of a general broadside-coupled coplanar waveguide for (M)MIC applications," Transaction on Microwave Theory and Techniques, vol. 37, May. 1989, pp. 843-850.
- [13] K. Park, K. Kim, J. Lim, and D. Ahn, "A new open stubs structure of Kuroda low-pass filter using DGS," Proc. WAMICON '09, IEEE 10<sup>th</sup> Annual, Apr. 2009, pp. 1-4.
- [14] H. Lin, X. Chen, X. Shi, L. Chen, and Y. Bai, "A wide stopband CPW low pass filter using quarter wavelength stepped impedance resonators," Proc. ICMMT Conf., May. 2010, pp. 62-65.



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