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DESIGN OF QUAD-BAND FILTER BASED ON THE IMPROVED VERSIONS OF DCRLH CELL

K. Lu*, **T. Xu, and X.-Q. Yao**

Missile Institute, Air Force Engineering University, Sanyuan 713800, China

Abstract—In this article, a realization version of quad-band filter is firstly proposed, and it is the cascaded structure composed of the shunt open-circuit DCRLH (dual composite right/left-handed) cell and the shunt short-circuit DCRLH cell. The above two cells are initially proposed here in order to improve the inherent limitations of the microstrip DCRLH cell. It is demonstrated that the matching performance and frequency selectivity of these two cells are both better than those of the microstrip DCRLH cell. It is more important that both the cells exhibit three transmission zeros within the given frequency band, and any of them is of great potential to be applied in the design of quad-band filters. In order to get sufficient design freedom, we utilize the cascade connection version based on the shunt open/short-circuit DCRLH cells. Whereas, only the first and second transmission zeros of both the shunt open/short-circuit DCRLH cells are explored. Both the simulated and measured results indicate that the proposed design method is right and effective.

1. INTRODUCTION

Most of the modern RF/microwave equipments are designed to operate in the dual-bands or even multi-bands, such as GPRS system and GPS satellite system. Although broadband components are also usable in some of these applications, they cannot suppress the disturbances effectively in the whole frequency band. Moreover, the multi-band components can reduce the number of elements, save the space and lower the power consumption. Excluding the dual-band elements, the tri-band components in multi-band research are extensively

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* Corresponding author: Ke Lu (lookluna@126.com).

investigated, such as tri-band antennas [1], tri-band filter [2] and tri-band transmitter [3]. The design method to control every operating band with sufficient freedom is the key in the design of multi-band components. Meanwhile, the design difficulties are enhanced to great extent with the increase of the number of the operating bands. Thus, the investigation on the quad-band components is rather rare. At present, the investigation on quad-band antenna [4] and quad-band branch-line coupler [5] have been implemented. Moreover, the concept of extended composite right/left-handed (ECRLH) has been proposed to provide a novel method to design the quad-band components [6, 7]. ECRLH inherently exhibits two left-handed passband and two right-handed passbands. From the lower frequency band to the higher frequency band, these passbands are left-handed, right-handed, left-handed and right-handed ones, respectively. Then, several special realizations of ECRLH have been proposed [8, 9]. In [8], the quad-band impedance inverter, quad-band power divider and quad-band branch-line coupler based on ECRLH are investigated systematically. Whereas, the quad-band filter cannot be designed utilizing ECRLH, because there is no gap between the left-handed passband and the right-handed passband in the lower frequency band and the higher frequency band, respectively. Thus, dual-band filter is achieved utilizing the above magnitude property of ECRLH. Until now, only [6] has proposed one circuit model of the shunt open-circuit ECRLH to design the quad-band filter, but no realization has been proposed. In both [10] and [11], through electromagnetic coupling, the dual resonant mode property of the stepped impedance resonator is utilized to design the quad-band bandpass filters.

In this article, we propose a novel method based on the shunt open/short-circuit DCRLH cells to design the quad-band filter. It is found that a microstrip realization of DCRLH has the disadvantages of poor matching condition, low frequency selectivity and limited adjustment range. To solve the above limitations, we proposed shunt open-circuit DCRLH cell and shunt short-circuit DCRLH cell. It is demonstrated that the matching condition, frequency selectivity and adjustment range of these two cells are both superior to those of DCRLH cell. More importantly, both the cells exhibit multi-band property. Then, the design guidelines to control the multi-band property are investigated through parametric analysis. To explore the given property, the cascaded structure composed of the shunt open-circuit DCRLH cell and shunt short-circuit DCRLH cell is proposed to design quad-band filter. Both simulated and measured results indicate that the proposed design method is effective and right.

2. IMPROVEMENT OF DCRLH CELL

DCRLH cell is the dual version of the composite right/left handed (CRLH) cell which plays an extremely important role in the metamaterial research. The concept of DCRLH is initially proposed in 2006 [12]. DCRLH exhibits the left-handed passband in higher frequency band and the right-handed passband in lower frequency band while CRLH exhibits the left-handed passband in lower frequency band and right-handed passband in higher passband. Until now, several realization versions of DCRLH have been proposed [13–15]. In these versions, the microstrip DCRLH has the advantages of easy fabrication and simple design. As a result, the microstrip version is attracting more and more attention. Its geometrical structure is depicted in Figure 1(a). The microstrip version is composed of one interdigital capacitor, one narrow microstrip line parallel to the given interdigital capacitor, rectangular patch and shunt narrow microstrip line. To display clearly, only single shunt part is included in Figure 1(a). In fact, two shunt parts are always utilized for symmetry which will not change the basic operating principle. For simplicity, $DlcW2 = DlcW1$,

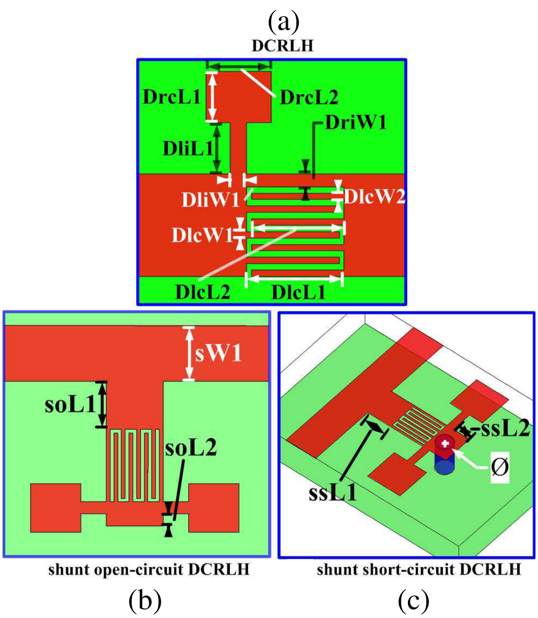


Figure 1. Configuration of (a) DCRH cell, (b), (c) shunt open/short-circuit DCRLH cell.

$DlcL2 = DlcL1 - 0.2\,\text{mm}$ and $DrcL1 = DrcL2$ are kept throughout. Additionally, the substrate with relative dielectric constant of 2.2 and thickness of 1.5 mm is utilized in both simulation and fabrication.

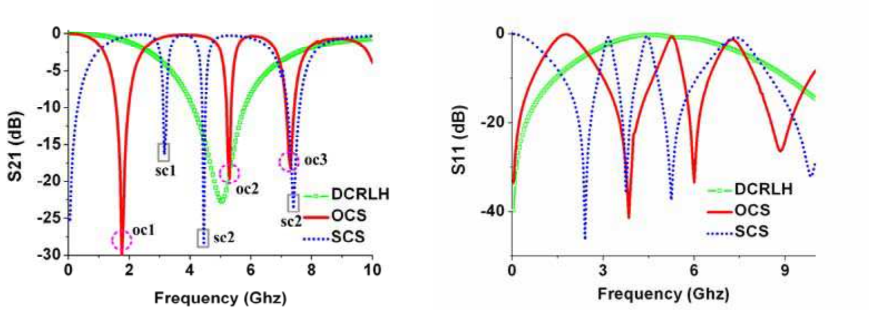
The microstrip DCRLH is just preliminarily investigated, and its property has not been explored thoroughly and individually. In this article, through systematical parametric analysis, it is found that its performance is quite sensitive to *DliW1* and *DliL1*. Its property is difficult to adjust further when *DliW1* is close to 0.1 mm which is our minimized achievable fabrication tolerance. On the other hand, the effective area of the microstrip DCRLH cell will enlarge greatly with the increase of *DliL1*. Thus, the design arbitrariness is rather limited. Simultaneously, the inherent dual-band property of DCRLH is still not appropriate for designing quad-band filters. It is reasonable to conclude that the microstrip DCRLH cannot be explored directly to design quad-band filters.

According to the transmission line theory, the input impedances of the open-circuit and short-circuit transmission lines can be expressed as in Equations (1) and (2), respectively.

$$Z_{in}^{oc}(d) = -jZ_0\text{ctg}(\beta d) \tag{1}$$

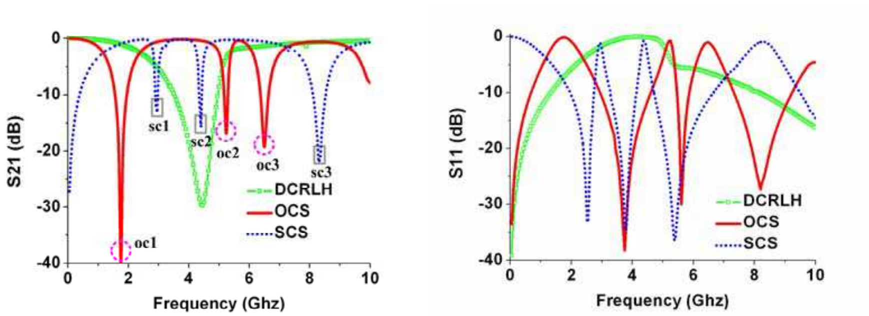
$$Z_{in}^{sc}(d) = jZ_0\text{tg}(\beta d) \tag{2}$$

where d denotes the physical length of the given transmission line; the superscript 'oc' is the abbreviation of open-circuit; 'sc' is the abbreviation of short-circuit; the subscript 'in' is the abbreviation of input. When $d = \lambda/4$, the input impedance of open-circuit transmission line is equal to zero where λ is the wavelength at the frequency of f_0. Thus, $\lambda/4$ open-circuit stub exhibits one transmission zero at f_0. On the other hand, the put impedance of short-circuit transmission line is infinitely large when $d = \lambda/4$, and $\lambda/4$ short-circuit stub exhibits one transmission pole. By replacing the shunt parts of both open/short-circuit stubs with DCRLH cells, two prototypes shown in Figures 1(b) and 1(c) are achieved and they are named by shunt open-circuit DCRLH cell and shunt short-circuit DCRLH cell, respectively. Based on the above principles, it is expected that the shunt open-circuit DCRLH cell exhibits bandstop property at the frequency with −90 degrees phase shift for DCRLH cell. Meanwhile, it is expected that the shunt short-circuit DCRLH cell exhibits bandpass property at the same frequency point. These expectations are verified by the comparisons implemented by full-wave simulation. To demonstrate that the properties are common, two groups of comparisons are explored, and the results are depicted in Figures 2 and 3, respectively. In simulation, $soL1 = 6\,\text{mm}$, $soL2 = 1.5\,\text{mm}$ are kept constant. In case 1, $DrcL1 = 5.0\,\text{mm}$, $DliL1 = 4.0\,\text{mm}$, $DliW1 = 2.5\,\text{mm}$, $DlcW1 = 0.3\,\text{mm}$, $DriW1 = 0.3\,\text{mm}$, $DlcL1 =$



(a) S_{21} (b) S_{11}

Figure 2. Comparison results in case 1.



(a) S_{21} (b) S_{11}

Figure 3. Comparison results in case 2.

5 mm, $DlcL2 = 4.8$ mm. In case 2, $DliW1 = 1$ mm, $DlcL1 = 5.1$ mm, $DlcL2 = 4.9$ mm and the other parameters are identical to the ones in case 1. In these two figures, 'OCS' denotes the shunt open-circuit DCRLH cell and 'SCS' the shunt short-circuit DCRLH cell.

As shown in these two figures, within the given frequency band, the shunt open-circuit DCRLH cell exhibits three transmission zeros, denoted as '$oc1$', '$oc2$' and '$oc2$'. Meanwhile, the shunt short-circuit DCRLH cell also exhibits three transmission zeros, denoted as '$sc1$', '$sc2$' and '$sc3$'. It is obvious that these two cells are of great potential to the design of quad-band components. In both cases, the transmission zeros of shunt open-circuit DCRLH cell and transmission poles approximately correspond to the frequency points with ± 90 degrees phase shift for DCRLH cell (for simplicity, these frequency points are not shown in details). With the increase of frequency, the error between the transmission zeros and the given frequency points becomes more and more obvious. The reason may be that the electrical length of the microstrip line which connects DCRLH cell and the main transmission line cannot be ignored when the frequency becomes high enough. Based on the above results, it is demonstrated that our expectation is right and effective. On the other hand, the matching condition and frequency selectivity of passbands or stopbands for the shunt open/short-circuit DCRLH cells are both superior to those of DCRLH cell, and these excellent performances are achieved without any optimization.

3. DESIGN OF THE SHUNT OPEN/SHORT-CIRCUIT DCRLH CELLS

According to the results in above section, both the shunt open/short-circuit DCRLH cells exhibit three transmission zeros, and their properties are qualified to design the quad-band filter to some extent. But for any of these two cells, it is quite difficult to get sufficient design freedom to control every passband independently within the wide band. In this article, we propose a cascaded prototype composed of the shunt open/short-circuit DCRLH cells shown in Figure 4. The proposed prototype primarily utilizes the first and second transmission zeros of both of these two cells to get the quad-band property. Thus, the difficulty in design procedure is greatly alleviated. Next, the design rules on the first and second transmission zeros of the two cells are investigated through parametric analysis. It is found that the second transmission zero can be independently controlled through *DlcL1*, and the results of parametric analysis are depicted in Figure 5. As shown in Figure 4, *DlcL1* influences the second transmission zeros of both cells greatly and almost has no effect on the first transmission zeros. With the increase of *DlcL1*, the second transmission zeros move downwards. It means that the second transmission zeros can be

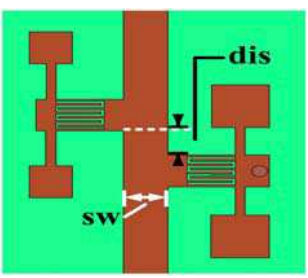


Figure 4. Configuration of the proposed quad-band filter.

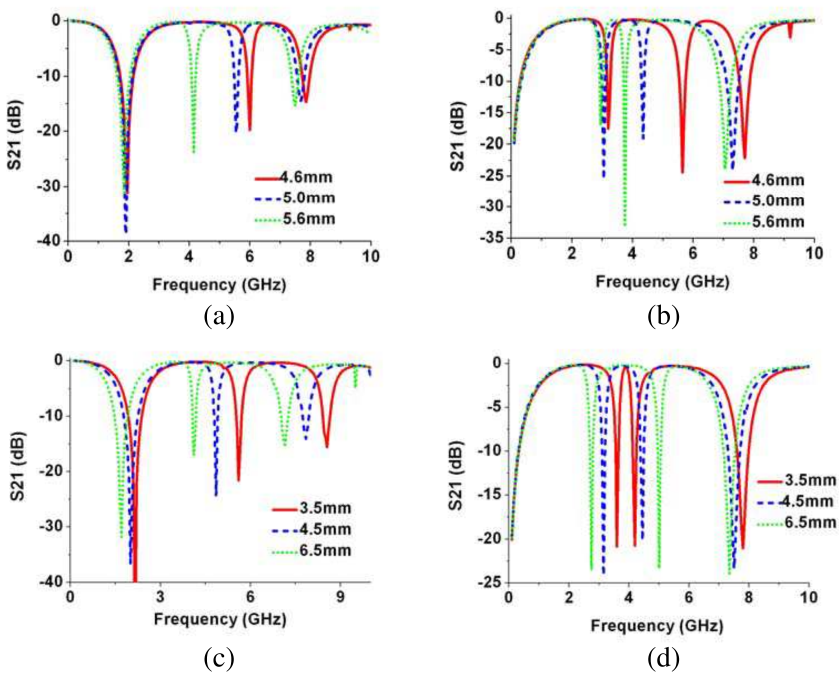


Figure 5. Effect of *DlcL1* on the first and second transmission zeros. (a) Shunt open-circuit DCRLH cell. (b) Shunt short-circuit DCRLH cell. (c) Shunt open-circuit DCRLH cell. (d) Shunt short-circuit DCRLH cell.

controlled effectively and independently through *DlcL1*. In addition, it is found that the first transmission zeros of both cells are only sensitive to the geometrical parameter, *DrcL1*. As shown in Figure 6, the first transmission zeros move downwards with the increase of *DrcL1*. Whereas, this parameter also influences the second transmission zeros greatly. It means that the first transmission zeros can be controlled effectively but not independently.

4. DESIGN AND FABRICATION OF THE QUAD-BAND FILTER

On the basis of the above investigation, one quad-band filter shown in Figure 3 is designed to verify that the proposed design method is effective and right. Firstly, the shunt open/short-circuit DCRLH cells are simulated individually. Their performance is compared in

Figure 6. For the shunt open-circuit DCRLH cell, its geometrical parameters are as following: $DrcL1 = 6.0\,\text{mm}$, $DliL1 = 5.0\,\text{mm}$, $DliW1 = 2.5\,\text{mm}$, $DlcW1 = 0.3\,\text{mm}$, $DriW1 = 0.3\,\text{mm}$, $DlcL1 = 5.0\,\text{mm}$, $DlcL2 = 4.7\,\text{mm}$, $soL1 = 4.5\,\text{mm}$, $soL2 = 2\,\text{mm}$. For the shunt short-circuit DCRLH cell, its geometrical parameters are as following: $DrcL1 = 6.5\,\text{mm}$, $DliL1 = 4.0\,\text{mm}$, $DliW1 = 1.0\,\text{mm}$, $DlcW1 = 0.3\,\text{mm}$, $DriW1 = 0.3\,\text{mm}$, $DlcL1 = 9.0\,\text{mm}$, $DlcL2 = 8.7\,\text{mm}$, $ssL1 = 2.5\,\text{mm}$, $ssL2 = 4.5\,\text{mm}$.

It is expected that the superposition from the passbands of the shunt open-circuit DCRLH cell and shunt short-circuit DCRLH cell will generate passbands of the proposed quad-band filter. These frequency bands are denoted in Figure 6 with light colored rectangle. Then, the synthesized design procedure is implemented, and the given results are depicted in Figure 7. In the synthesized model, $dis = 1.4\,\text{mm}$, $sw = 4.6\,\text{mm}$. The given results indicate that the results from the synthesized design procedure approximately verify the

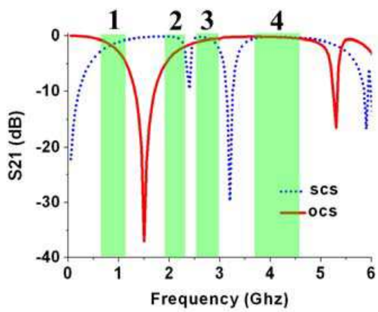


Figure 6. Comparison of the performance for individual cells.

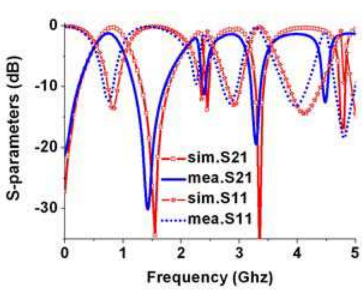


Figure 7. Simulated and measured results.

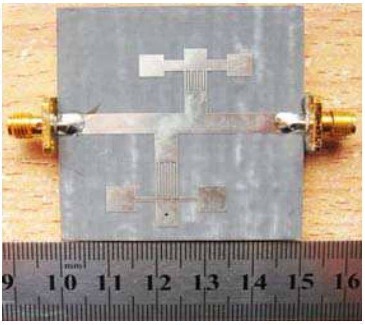


Figure 8. Photograph of the fabricated prototype.

expectation deriving from the individual simulation shown in Figure 6. Consequently, the proposed prototype is fabricated and measured. The measured results are depicted in Figure 7, and a photograph of the fabricated prototype is shown in Figure 8. The given results indicate that the proposed prototype surely exhibits the quad-band property. The simulated and measured results roughly agree well. Thus, it is demonstrated that the proposed design method of quad-band filter is right and effective.

5. CONCLUSIONS

We firstly propose one novel method based on the shunt open/short-circuit DCRLH cells to design the quad-band filter. The shunt open/short-circuit DCRLH cells are derived from the microstrip DCRLH cell whose inherent dual-band property is not suitable for the quad-band filter. Compared with DCRLH cell, the shunt open/short-circuit DCRLH cells exhibit not only excellent performance but also three transmission zeros, namely multi-band property. In our design, the cascaded structure composed of the shunt open/short-circuit DCRLH cells is explored to provide sufficient design freedom. In fact, only the first and second transmission zeros of these two cells are explored. The effectiveness of the proposed design method is verified by both the simulation and measurement.

REFERENCES

1. Zhou, Y., C.-C. Chen, and J. L. Volakis, "Stacked patch antenna for tri-band GPS applications," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 55, No. 1, 220–223, 2007.
2. Lee, C.-H., C.-I. G. Hsu, and H.-K. Jhuang, "Design of a new tri-band microstrip BPF using combined quarter-wavelength SIRs," *IEEE Microwave and Wireless Component Letters*, Vol. 16, No. 11, 594–596, 2006.
3. Lin, Y.-S., C.-C. Liu, K.-M. Li, and C. H. Chen, "Design of an LTCC tri-band transceiver module for GPRS mobile applications," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 52, No. 12, 2718–2724, 2004.
4. Chiu, C.-W., C.-H. Chang, and Y.-J. Chi, "Multiband folded loop antenna for smart phones," *Progress In Electromagnetics Research*, Vol. 102, 213–226, 2010.
5. Tang, C.-W., "Design of multipassband microstrip branch-line

couplers with open stubs," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 57, No. 1, 196–204, 2009.

6. Rennings, A., S. Otto, J. Mosig, C. Caloz, and I. Wolff, "Extended composite right/left-handed (E-CRLH) metamaterial and its application as quadband quarter-wavelength transmission line," *Proceedings of Asia-Pacific Microwave Conference*, 2006.
7. Eleftheriades, G. V., "A generalized negative-refractive-index transmission-line (NRI-TL) metamaterial for dual-band and quad-band applications," *IEEE Microwave and Wireless Component Letters*, Vol. 7, No. 6, 415–417, 2007.
8. Durán-Sindreu, M., G. Sisó, J. Bonache, and F. Martín, "Planar multi-band microwave components based on the generalized composite right/left handed transmission line concept," *IEEE Transactions on Microwave Theory and Techniques*, Vol. 58, No. 12, 3882–3891, 2010.
9. Qiang, L., Y.-J. Zhao, W. Zhao, Q. Sun, and B. Liu, "Extended dual composite right/left-handed transmission line," *Microwave and Optical Technology Letters*, Vol. 52, No. 12, 2838–2840, 2010.
10. Yang, R.-Y., C.-Y. Hung, and J.-S. Lin, "Design and fabrication of a quad-band bandpass filter using multi-layered SIR structure," *Progress In Electromagnetics Research*, Vol. 114, 457–468, 2011.
11. Yang, C.-F., Y.-C. Chen, C.-Y. Kung, J.-J. Lin, and T.-P. Sun, "Design and fabrication of a compact quad-band bandpass filter using two different parallel positioned resonators," *Progress In Electromagnetics Research*, Vol. 115, 159–172, 2011.
12. Caloz, C., "Dual composite right/left-handed (D-CRLH) transmission line metamaterial," *IEEE Microwave and Wireless Component Letters*, Vol. 16, No. 11, 585–687, 2006.
13. Caloz, C. and H. V. Nguyen, "Novel broadband conventional and dual-composite right/left-handed (C/D-CRLH) metamaterials: Properties, implementation and double-band coupler application," *Applied Physics A — Materials Science & Processing*, Vol. 87, 309–316, 2007.
14. Ryu, Y.-H., J.-H. Park, J.-H. Lee, J.-Y. Kim, and H.-S. Tae, "DGS dual composite right/left handed transmission line," *IEEE Microwave and Wireless Component Letters*, Vol. 18, No. 7, 434–436, 2008.
15. Tong, W., Z. Hu, and H. Zhang, "Study and realisation of dual-composite right/left-handed coplanar waveguide metamaterial in MMIC technology," *IET Microwaves, Antennas & Propagation*, Vol. 2, No. 7, 731–736, 2008.