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Compact UHF 9th-Order Bandpass Filter with Sharp Skirt by Cascaded-Triplet CRLH-ZOR

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Abstract – We propose a compact high-order(9th) UHF bandpass filter comprising the composite right-handed and left-handed(CRLH) zeroth-order resonators(ZORs) in the form of the three cascaded-triplets(CTs) newly applied to the ZOR filter which results in very steep skirt. The method is verified by circuit and EM simulations and measurement with metamaterial properties.

Keywords: ZOR, Bandpass filter, Miniaturization, Cascaded Triplet, High channel selectivity

1. Introduction

High channel selectivity is realized by bandpass filters with sharp skirt. The order of a filter is increased, and more resonators or modes are adopted and cascaded in groups with cross-coupling paths(CCPs) to maximize the skirt slope[1-6]. Transmission-line(TL) resonators are basically half-wavelength or quarter-wavelength with a load, and make their filters elongated conspicuously for an increased skirt slope. But, their footprints can be saved by changing one-half wavelength resonator to a stepped impedance segment resonator(SIR), taking more stages and folding them for CCPs as [5, 6]. The SIR is a good choice to widen the stopband, but cannot guarantee the improved skirt slope, and is a very common technique. The skirt slopes look similar to order 2 through 5 in [5, 6], but are not sufficient to be called high channel selectivity. While the filter performance gets improved, it is expected that the growth of its physical size needs to be suppressed. As the effective means to design compact RF components, the CRLH lines and ZOR of lumped elements were suggested by Caloz et al in [7], the no-phase variation phenomenon as β=0 and non-linear dispersion relation have been used to design sub-wavelength resonators and compact filters [8-13]. The CRLH ZOR filters in [8, 10] and ENZ filter [9] show improvement in reducing the sizes as well as insertion loss.

In this paper, a compact CRLH ZOR bandpass filter is designed to have remarkably enhanced frequency selectivity working in the UHF band. Firstly, the nonlumped fully-printed ZORs for the 9th-order in-line CT bandpass filter are designed. Secondly, we show steep skirt due to the CT blocks each of which provides the phase-difference type of cross-coupling in every three neighboring ZORs of the filter, which creates transmission zeros(TZs) in the proximity of the passband edges. And it is folded to save the footprint more. Working with these procedures, a higher slope of skirt from the passband to the stopband can be achieved by using a smaller physical structure. To examine the validity of the proposed design method, the circuit and 3D electromagnetic(EM) simulations are carried out and compared to the measurement of the FR4-based fabrication of the CT CRLH ZOR bandpass filter. Especially, the advantages of the proposed filter will be presented by a check that this 9th-order filter smaller than others has the skirt slope as sharp as a 15th-order Chebyshev filter.

2. Design of the ZORs of the In-line CT Bandpass Filter

A bandpass filter for a GSM band communication repeater system is designed on the basis of the following specifications: center freq.(f_0), bandwidth(BW), insertion loss, return loss, and sharp skirt (Attenuation at f_{ue}+40 MHz) are 900MHz, 160MHz, ≤9.0dB, ≤-12dB, and ≥+40dB, respectively. The spec. on the insertion loss does not look tight, because it is generated by considering a circuit on the $2\lambda_0$-long FR4 substrate. The insertion loss can be compensated for the placement of an amplifier. Especially, the main concern in this design is the high channel selectivity as 40 dB near the f_{ue} as the band upper edge which is f_0 + BW/2. The skirt improvement will be addressed later, and the passband is formed firstly. The schematic of the in-line ZOR bandpass filter is.

The equivalent circuit in Fig. 1(a) comprises resonators 1 through 9 and their coupling elements named $IRC_{i,j}$. Instead of $\lambda_0/2$ resonators, we use the CRLH ZOR for each of the shunt resonators in Fig. 1(b) that are coupled through the inductive connection $IRC_{i,j}$ as the way of [8-10]. CCP_{13} bridges resonators 1 and 3. CCP_{46} and CCP_{79} couple across resonators 4 and 6, and 7 and 9, respectively. The role of CCPs will be mentioned with the phase-cancellation of admittance in the later section. To find the circuit elements L_R, C_R, L_L and C_L for each resonator as Fig. 1(c), the

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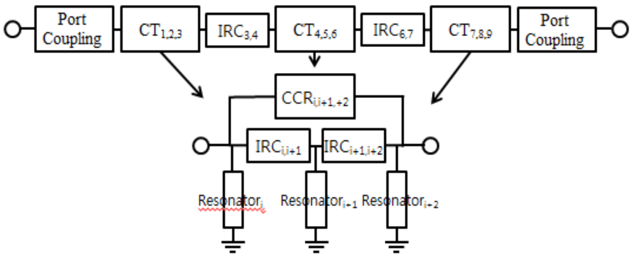
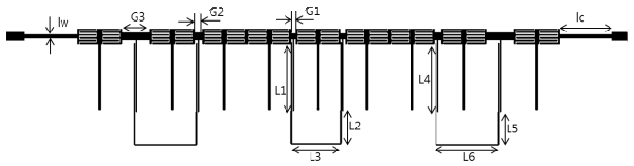
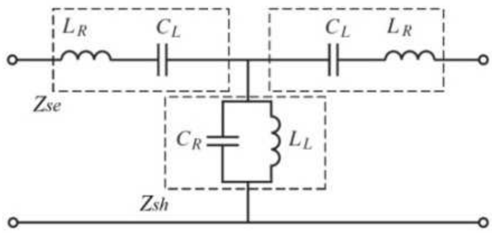


(a) Equivalent circuit of the proposed in-line CT bandpass filter



(b) Physical shape of the proposed in-line CT bandpass filter



(c) Equivalent circuit for the ZOR for the proposed in-line CT bandpass filter

Fig. 1. The equivalent circuit and physical shape of the proposed 9th–order in-line CT bandpass filter

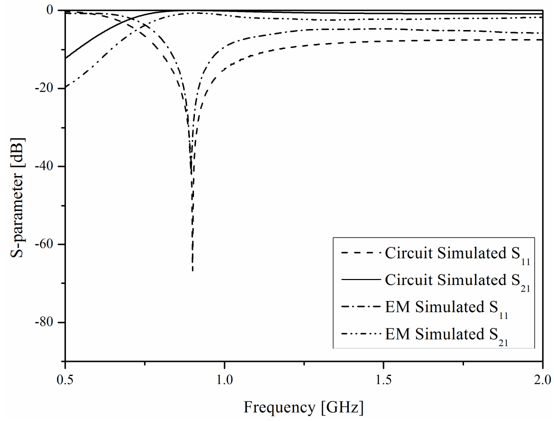
following equations on the cut-off frequencies, center frequency and impedance of the CRLH ZOR are solved.

$$\omega_L = \frac{1}{\sqrt{L_L C_L}}, \quad \omega_R = \frac{1}{\sqrt{L_R C_R}}, \quad \omega_{se} = \frac{1}{\sqrt{L_R C_L}}$$

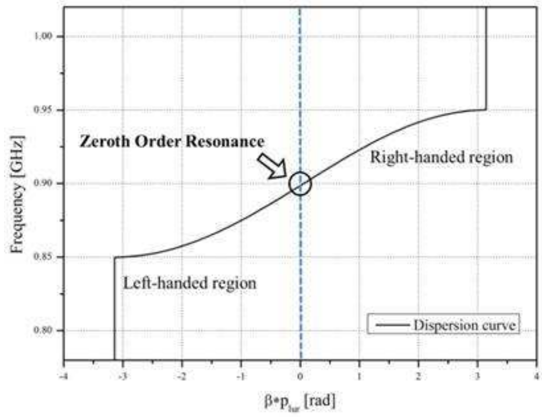
$$\omega_{sh} = \frac{1}{\sqrt{L_L C_R}}, \quad \omega_0 = \sqrt{\omega_R \omega_L} \tag{1}$$

where subscripts R, L, se and sh mean the right-handed, left-handed, series and shunt, in that order.

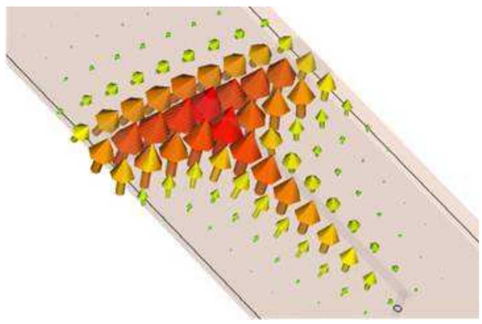
For resonator 1, we obtain C_L = 0.492 pF, C_R = 4.494 pF, L_L = 5.682 nH, and L_R = 0.697 nH with IRC of 2.97nH, and the elements for the other ZORs are calculated in the same manner. The circuit elements are converted to the initial values of the physical dimensions using Eqs. (6-9) in [8], considering the microstrip with the 50 mil thick substrate of relative dielectric constant 4.4 and loss tangent of 0.02. And then, the physical dimensions are varied from the initial values in the 3D EM simulation and reach the final values, when they give the center frequency at the desired value (900 MHz). They are L1 = L4 = 18.6mm, L2 = L5 = 10mm, L3 = 15.2mm, L6 = 18.9mm, G1 = 1.4mm, G2 = 2.2mm, G3 = 8mm, lc = 40mm, lw = 1mm and the FR4 substrate of ε_r = 4.4 in Fig. 1(b), and s-parameters S_{21} and S_{11} as the frequency response of the ZOR are achieved along with metamaterial properties as in Fig. 2



(a) S_{21} and S_{11} of the CRLH ZOR



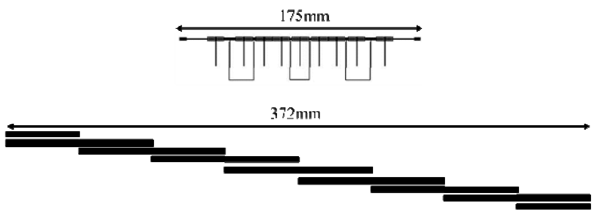
(b) Dispersion diagram of the CRLH ZOR



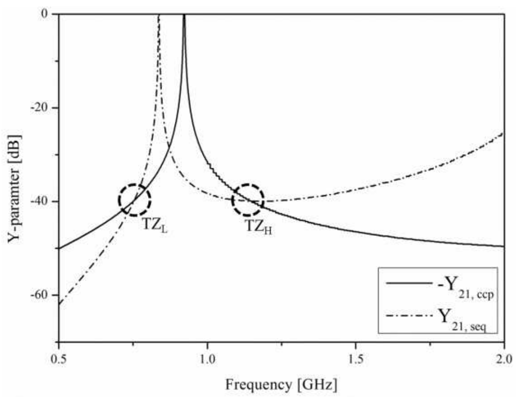
(c) Zeroth-order resonance electric field distribution at f_0 of the CRLH ZOR

Fig. 2. S_{21}, S_{11}, dispersion diagram, and field distribution of the CRLH ZOR

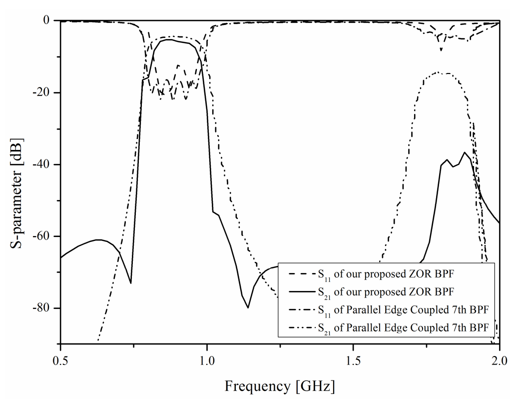
Fig. 2(a) reveals that the ZOR is appropriately implemented to resonate at f_0, and the circuit simulation agrees well with the 3D EM analysis result of the ZOR whose size is λ_g /20 (with respect to f_0). It is noted that this is the resonator level, and the complete passband will be made in the level of the filter. Fig. 2(b) is the dispersion diagram which has β times the unit-cell length vs. frequency, and shows β = 0 as the ZOR coinciding with f_0. Besides, the right- and left-handed regions occur beyond and below the ZOR as the positive and negative β, respectively. Together with the dispersion diagram, another property of this CRLH metamaterial structure is given in Fig. 2(c) as the in-phase electric field. In other words, all the field vectors of β = 0 have the same direction at the ZOR frequency point.



(a) Size of our 9th-order in-line CT ZOR filter, compared with a 7th-order parallel edge coupled filter



(b) $Y_{21,\,seq}$ and $-Y_{21,ccp}$ of the sequential and cross-coupling paths for the proposed CT ZOR filter



(c) S_{21} and S_{11} of our 9th-order in-line CT ZOR filter compared to a 7th-order parallel edge coupled filter

Fig. 3. Geometry, path admittances, and S_{21} and S_{11} of the our in-line CRLH ZOR filter

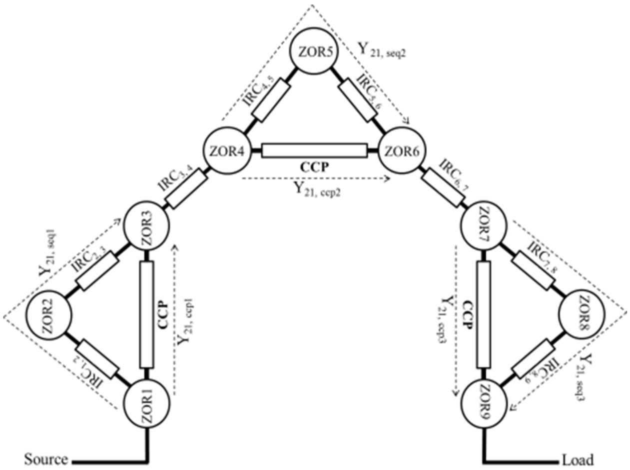
3. Proposed CT ZOR bandpass filter and its Folded Structure

Using the ZORs and coupling elements and cross-coupling paths, the filter is realized as Fig. 3.

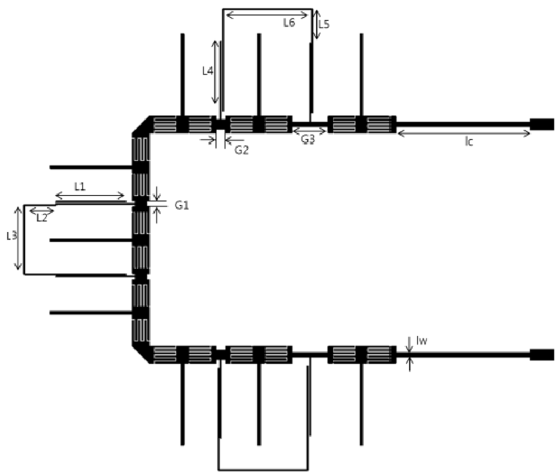
The in-line filter in Fig. 3(a) has 9 ZORs proposed with the coupling elements to effectively miniaturize the overall size. In detail, the total length of the proposed in-line filter is 175mm, shorter than a lower ordered filter of the parallel edge coupled type that is 372mm long. This size reduction is also helpful to lowering the insertion loss of S_{21}. As a note, when a steeper skirt is required, since one ZOR itself is not directly concerned with it, the interaction between ZORs should be taken into account to have transmission zeros. Particularly, the cross-coupling over non-adjacent ZORs can be the key to increasing the skirt slope. Of course, if the size of a resonator for a filter is as small as possible, more resonators can be put and incorporated to raise the filter order in a physically confined area. Therefore, the ZOR is indirectly related to the determination of the slope skirt. Prior to s-parameters, the function of the CCPs made up of L1, L2, L3, L4, L5, and L6 is addressed. The CCP and sequential path in a CT are needed for transmission zeros to steepen the slop of skirt. For this, the sum of the admittance from the CCP and sequential path should become zero at a target TZ in terms of phase cancellation. So, the admittance of the sequential path $Y_{21,seq}$ should equal $-Y_{21,ccp}$ at the TZ frequencies for CCP_{13}, CCP_{46} and CCP_{79} from the three CTs, as shown in Fig. 3(b). This results in the improved channel selectivity with TZs as presented in Fig. 3(c) with S_{21} = -58dB at f_{ue}+40MHz. Seeing the s-parameters, the loss of the FR4 substrate and conductor is accumulated, and the insertion loss of the proposed 9th-order filter is 5.7 dB, which is similar to that of the compared 7th-order filter. Next, the proposed filter is manufactured.

Before the fabrication, a further work is performed to reduce the footprint of the 9th-order CT ZOR filter by folding the physical structure. This is illustrated with the topological schematic as follows.

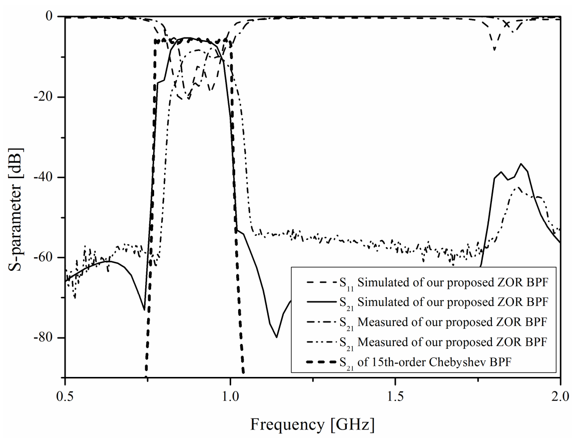
Though the in-line configuration is folded, the frequency response should not change. So, Fig. 1(a) can be modified to the topological schematic of Fig. 4(a) where the resonators are expressed as circular nodes. Three CTs are shown and each CT consists of three nodes. This is physically implemented as Fig. 4(b) as the folded version of Fig. 3(a). The folded CT ZOR filter is smaller than 1/7 of the parallel edge coupled geometry. The fabricated filter presents the frequency response similar to the EM simulated result in Fig. 4(c) except for the frequency shift of approximately 40 MHz and the insertion loss increased by roughly 3 dB. This error is guessed to result from the possible irregularity in dielectric constant and loss tangent, impedance mismatch due to soldering the interconnection, etc. Finally, to know the filter-order equivalent to the



(a) Topological schematic of the folded CT ZOR bandpass filter



(b) Top-view of the folded 9th-order CT ZOR bandpass filter



(c) Simulated and measured S_{21} and S_{11} of the folded CT ZOR filter compared with the 15th-order transfer function

Fig. 4. Topology and physical structure of the folded CT ZOR filter and comparison between simulated and measured S_{21} and S_{11}

proposed filter, we calculate the transfer function ($S_{21}^{conv.}(s)$) that follows the achieved skirt-slope.

$$S_{21}^{conv.}(s) = \frac{b_{14}s^{14} + b_{13}s^{13} + \cdots + b_2 s^2 + b_1 s + b_0}{s^{15} + a_{14}s^{14} + \cdots + a_2 s^2 + a_1 s + a_0} \quad (2)$$

where the coefficients are $a_{14} = 0.9121$, $a_{13} = 4.172$, $a_{12} = 3.246$, $a_{11} = 6.955$, $a_{10} = 4.536$, $a_9 = 5.905$, $a_8 = 3.14$, $a_7 = 2.686$, $a_6 = 1.115$, $a_5 = 0.6281$, $a_4 = 0.1883$, $a_3 = 0.06491$, $a_2 = 0.01191$, $a_1 = 0.001947$, $a_0 = 0.0001227$, $b_{14} = b_{13} = b_{12} = b_{11} = b_{10} = b_9 = b_8 = b_7 = b_6 = b_5 = b_4 = b_3 = b_2 = b_1 = 0.0$ and $b_0 = 0.0001227$.

This is plotted in Fig. 4(c) and compared to our proposed filter. Therefore, it is uncovered that the slope of the 15th-order conventional Chebyshev filter is the closest to our proposed filter. In other words, our proposed filter has 9 resonators but its effect is equivalent to 15 resonators.

4. Conclusion

This paper proposed a novel bandpass filter made very compact by implementing the CRLH ZORs and their coupling, and forming a CT to have a steep skirt for high channel selectivity. Firstly, the resonators and their in-line CT ZOR bandpass filter were designed whose total size is nearly 0.34 of the parallel-edge coupled filter. Secondly, TZs were provided for improving the skirt of the initial ZOR filter. Besides we could reduce the footprint of the filter by folding, and have the skirt as steep as a 15th-order Chebyshev filter, respectively. The simulation and measurement validated the proposed design method, and the CRLH ZOR properties were proven by the in-phase electric field and dispersion diagram.

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References

[1] R. Levy, “Direct Synthesis of Cascaded Quadruplet (CQ) Filters”, *IEEE Transactions on Microwave Theories and Techniques*, Vol. 13, pp.2940-2945, Dec. 1995.

[2] R. Hershtig, R.Levy, and K. Zaki, “Synthesis and Design Of Cascaded Trisection (CT) Dielectric Resonator Filters”, *Microwave Conference*, 27th European, pp.784-791, Sept. 1997.

[3] S. Kahng, M. Uhm, and S. Lee, "A Dual-Mode Narrow-Band Channel Filter and Group-Delay Equalizer for a Ka-Band Satellite Transponder", *ETRI Journal*, Vol. 25, No. 5, pp.379-386, June. 2006.
[4] M. V. Nedelchev, and I. G. Iliev, "Accurate Design of Triplet Microstrip Square Open-Loop Resonator Filters", *Microwave Review*, Vol. 12, pp. 36-40, Nov. 2006.
[5] C.-I G. Hsu, C.-H. Lee, and Y.-H. Hsieh, "Tri-Band Bandpass Filter With Sharp Passband Skirts Designed Using Tri-Section SIRs," *IEEE Microwave and Wireless Components Letters*, Vol. 18, No. 1, pp.19-21, Jan. 2008.
[6] C.-I. G. Hsu, C.-H. Lee, and H.-K. Jhuang, "Design of a novel quadband microstrip BPF using quarter-wavelength stepped-impedance resonators," *Microwave Journal,* Vol. 50, No. 2, pp. 102-112, Feb. 2007.
[7] C. Caloz, and T. Itoh, Electromagnetic metamaterials: Transmission line theory and microwave applications, Wiley-Interscience, 2006.
[8] G. Jang, and S. Kahng, "Design of a Dual-band Metamaterial Bandpass Filter Using Zeroth Order Resonance", *Progress in Electromagnetics Research C,* Vol. 7, pp.149-162, 2009.
[9] G. Jang, and S. Kahng, "Design of a Metamaterial Bandpass Filter Using the ZOR of a Modified Circular Mushroom Structure", *Microwave Journal,* Vol. 54, No. 5, pp. 158-167, May. 2011.
[10] G. Jang, and S. Kahng, "Compact metamaterial zeroth-order resonator bandpass filter for a UHF band and its stopband improvement by transmission zeros", *IET Microwaves, Antennas & Propagation IET,* Vol. 5, No. 10, pp. 1175-1181, July 2011.
[11] G. Jang, and S. Kahng, "Compact Composite Right-AND Left-Handed Bandpass Filter With Interlocked Gap coupling", *Microwave And Optical Technology Letters*, Vol. 55, No. 2, February 2013.
[12] D.-J. Eom, and S. Kahng, "Fully Printed Dual-Band Power Divider Miniaturized by CRLH Phase-Shift Lines", *Electronics & Telecommunication Research Institute Journal*, Vol. 35, No. 1, February 2013.
[13] B. Lee, and S. Kahng, "Compact UWB Bandpass Filter as Cascaded Center-Tapped CRLH Transmission-Line ZORs for Improved Stopband", *Journal of Electrical Engineering & Technology*, Vol. 8, No. 2, pp. 371-375, August 2013.

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