Progress In Electromagnetics Research C, Vol. 40, 25–35, 2013

COMPACT INTERDIGITAL CAPACITOR COUPLED DUAL-BEHAVIOR RESONATOR (ICDBR) FILTER WITH SUPPRESSION OF SPURIOUS RESPONSES

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Abstract—A compact interdigital capacitor coupled dual-behavior resonator (DBR) filter with high spurious responses suppression is proposed in this paper. The technique is based on two equivalent topologies of J-inverter and dual-line equivalent circuit of open-circuited stubs. The first compact equivalent topology capacitive inverter is a high pass structure, and consequently, the spurious responses can be suppressed effectively at low frequencies. The second equivalent topology π-network is employed in realizing a compact size and adding new transmission zeros dedicated to the spurious responses suppression at high frequencies. Further compactness is achieved with a dual-line equivalent circuit of open-circuited stubs. The relevant equations are given in the paper. Finally, a 3rd-order compact DBR filter is designed and measured. This structure has a high degree of miniaturization (83%) in comparison to the classical one. Measurement results show good agreement with the simulated ones.

1. INTRODUCTION

Planar filters have been widely used, such as coupled filters [1, 2] and stepped-impedance resonators with transmission zeros [3, 4]. They are attractive because of the planar structure and low fabrication cost. These considerations led us to pay attention to the dual behavior resonator (DBR) filter proposed in [5–8], which has many advantages, including independent control of the transmission zeros and central

Received 10 April 2013, Accepted 8 May 2013, Scheduled 17 May 2013
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frequency, low insertion loss, narrow band, high rejection level and simplicity in fabrication. However, its main drawbacks are also evident, large size and spurious responses on both sides of the central frequency. Several size reduction methods and spurious responses suppression techniques have been employed. A hybrid circuit using lumped elements miniaturizes the DBR filter effectively and is realized by a loading capacitor at the end of each open-circuited stub [9, 10], or connecting stubs with capacitors in series [11], but they both suffer from a poor Q factor and spurious responses. The integrating of low-pass structures [12–14] can suppress spurious response effectively and can be achieved by using capacitive-coupling [15, 16] instead of a 1/4 wavelength transmission line (J inverter), but these solutions do not achieve a compact size.

This paper presents a novel DBR filter with compact size and high spurious responses suppression at the same time, based on two equivalent topologies of J-inverter and dual-line equivalent circuit of open-circuited stubs. We describe here the new structure called interdigital capacitor coupled dual-behavior resonator (ICDBR) filter. The first equivalent topology capacitive inverter consists of a positive capacitor and two negative capacitors loaded on both ends, with the positive capacitor realized by an interdigital capacitor. As the interdigital capacitor is a high pass structure, the spurious responses can be suppressed at low frequencies (LF) effectively. The second equivalent topology π-network consists of a high impedance transmission line and two positive capacitors loaded on both ends. Both parallel negative and positive capacitances can be integrated into adjacent resonators except the outermost parallel capacitances for the source/load coupling. The open-circuited stubs with special lengths are used to achieve these capacitances and add new transmission zeros at the frequency of its 1/4 wavelength resonance, which suppress the high frequency spurious responses. The dual-line equivalent circuit is a replacement of open-circuited stubs.

Theoretical analysis and simulation of the new structure are given in Section 2. Fabrication and measurement are given in Section 3 and show a miniaturization percentage 83% and better spurious responses suppression than the classical one. Finally, Section 4 gives the conclusion.

2. THE METHOD AND DESIGN OF COMPACT DBR FILTER (ICDBR)

A classical DBR filter uses two parallel connected open-circuited stubs as shown in Fig. 1(a) to form a dual-behavior resonator [5, 6]. The equivalent impedance of each resonator (shown in Fig. 1(b)) is

$$Z = \frac{Z_{si1} Z_{si2}}{Z_{si1} + Z_{si2}} \tag{1}$$

where Z_{si1}, Z_{si2} are the input impedances of two open-circuited stubs. There are transmission zeros for each stub corresponding to $Z_{si1} = 0$ or $Z_{si2} = 0$, and transmission poles corresponding to $Z_{si1} + Z_{si2} = 0$. The resonators are connected with the quarter wavelength admittance inverters (J-inverter).

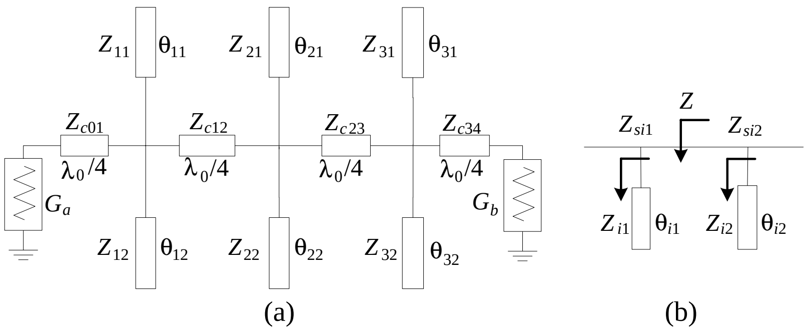

Figure 1. (a) A classical 3rd-order DBR filter schematic. (b) The basic resonator structure.

2.1. Two Equivalent Topologies of J-inverter

Two kinds of equivalent topologies of J inverter [17, 18] are employed and shown in Fig. 2, and in comparison to $\lambda_0/4$ transmission line

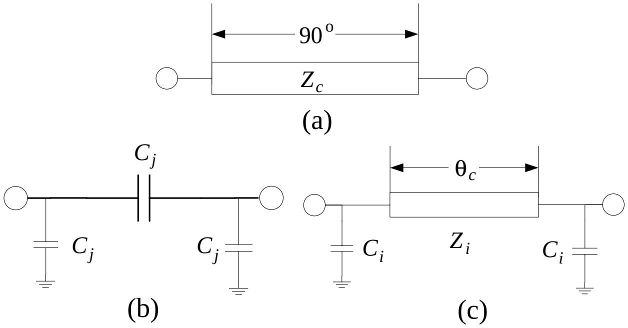

Figure 2. Two kinds of equivalent topologies of J inverter. (a) $\lambda_0/4$ transmission line (J inverter). (b) The first equivalent topology capacitive inverter. (c) The second topology Π-network.

(shown in Fig. 2(a)), they both have a compact horizontal size. The capacitive inverter (Fig. 2(b)) consists of a positive capacitor and two negative capacitors loaded on both ends, with the positive capacitor realized by an interdigital capacitor. The π-network (Fig. 2(c)) consists of a high impedance transmission line and positive capacitors loaded on both ends. Both parallel negative and positive capacitances can be integrated into adjacent DBR resonators except the outermost parallel capacitances for the source/load coupling.

The spurious responses of DBR filter near the central frequency are the transmission of non-resonating modes, where the LF and HF stubs both are non-resonant and present admittance in-phase. The power transmission occurs along the coupled transmission lines. Instead of using a $\lambda_0/4$ transmission line inverter, the capacitive inverter is a high pass structure and can suppress spurious responses in the LF band. The Π-network is used to provide new transmission zeros by realizing the parallel positive capacitors with open-circuited stubs, which suppress spurious responses in the HF band. So in these two equivalent topologies, a compact size and high spurious responses suppression are realized. The ICDBR filter design procedure is shown in Fig. 3, and the synthesis procedure is given as follows.

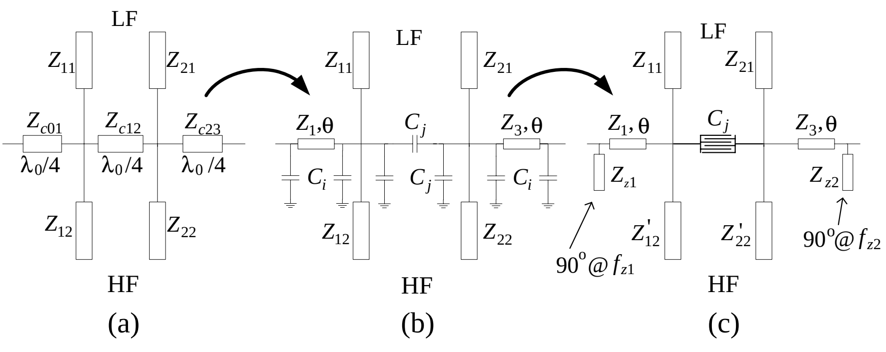

Figure 3. The design procedure of the ICDBR circuit with two equivalent topologies.

Owing to the synthesis developed in [6], the J-parameters lead to the $\lambda_0/4$ inverter parameters. Hence, the relation between the capacitive inverter and $J_{j,j+1}$ of the inverter at the central frequency f_0 is

$$C_j = \frac{J_{j,j+1}}{2\pi f_0 Z_0} \tag{2}$$

As $\lambda_0/4$ wavelength transmission line equals the Π-network circuit, we obtain (at f_0)

$$Z_i = \frac{Z_c}{\sin\theta_c}, \quad C_i = \frac{\cos\theta_c}{\omega Z_c} \tag{3}$$

As shown in Fig. 3, the parallel capacitances could be integrated into LF or HF stubs. Then, for a nth-order DBR filter, the new input admittance in Fig. 3(b) is

$$Y'_{in} = jY_{i2}\tan\theta + j\omega(\pm C_i \pm C_{i+1}) \tag{4}$$

The new access admittance of equivalent open-circuited stubs in Fig. 3(c) is

$$Y'_{in} = jY'_{i2}\tan\theta \tag{5}$$

Hence, at central frequency f_0, (5) is identical to (4), and we obtain (integrated into HF stubs)

$$Z'_{i2} = \frac{Z_{i2}\tan\theta_{i2}}{\tan\theta_{i2} + Z_{i2}\omega_0\left(\pm C_i \pm C_{i+1}\right)} \tag{6a}$$

Using the same method, we can obtain (integrated into LF stubs)

$$Z'_{i1} = \frac{Z_{i1}\tan\theta_{i1}}{\tan\theta_{i1} + Z_{i1}\omega_0\left(\pm C_i \pm C_{i+1}\right)} \tag{6b}$$

where θ_{i1}, θ_{i2} are the electrical lengths of LF and HF stubs at f_0.

2.2. Dual-line Equivalent Circuit of Open-circuited Stub

With the two equivalent topologies of J inverter, the horizontal dimension is reduced, but the vertical dimension remains the same. To achieve further miniaturization, the dual-line equivalent circuit of open-circuited stubs is shown in Fig. 4. Based on half angle formula, open-circuited stubs can be split into two parallel stubs, with half the length of the original stub, and the concise equations are given as follow

$$Y_{in} = jY_{i1,2}\tan(\theta) = j\frac{2Y_{i1,2}\tan(\theta/2)}{1-\tan^2(\theta/2)} = j2Y_{id}\tan\frac{\theta}{2} \tag{7}$$

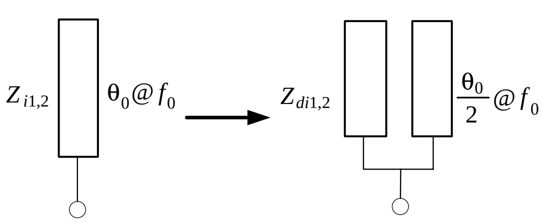

Figure 4. The dual-line equivalent circuit of open-circuited stubs.

where

$$Y_{i1,2d} = Y_{i1,2} \big/ \left(1 - \tan^2 (\theta/2)\right) \tag{8}$$

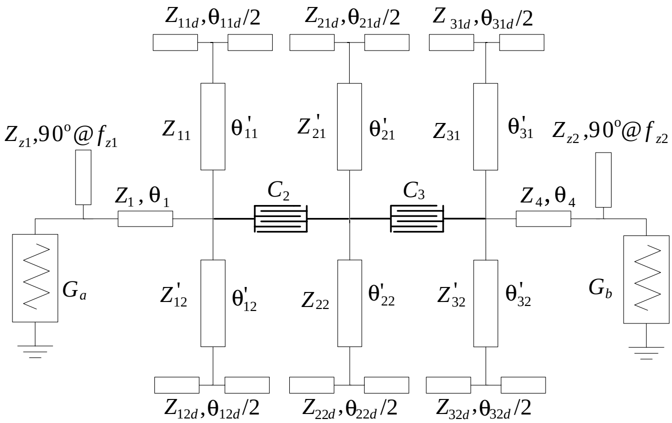

Figure 5. The compact DBR (ICDBR) filter with two equivalent topologies of J inverter and dual-line equivalent circuit of open-circuited stubs.

Table 1. Parameters of the ICDBR filter.

	Classical DBR (Ω)	Compact DBR filter (ICDBR) (Ω)
1st DBR	$Z_{11} = 65.1$, $Z_{12} = 100.7$ $\theta_{11} = 112.5^\circ$, $\theta_{12} = 75^\circ$	$Z_{11} = 65.1$, $Z'_{12} = 104.6$, $Z_{11d} = 33.2$, $Z_{12d} = 81.9$ $\theta'_{11} = 42.5^\circ$, $\theta_{11d} = 35^\circ$, $\theta'_{12} = 75^\circ$, $\theta_{12d} = 25^\circ$
2nd DBR	$Z_{21} = 89.3$, $Z_{22} = 114.3$ $\theta_{21} = 102.3^\circ$, $\theta_{22} = 80.4^\circ$	$Z'_{21} = 58.1$, $Z_{22} = 120.3$, $Z_{21d} = 38.4$, $Z_{22d} = 87.1$ $\theta'_{21} = 42.3^\circ$, $\theta_{12d} = 30^\circ$, $\theta'_{22} = 25^\circ$, $\theta_{22d} = 27.7^\circ$
3rd DBR	$Z_{31} = Z_{11}$, $Z_{32} = Z_{12}$	$Z_{31} = Z_{31}$, $Z'_{32} = Z'_{12}$ $Z_{31d} = Z_{11d}$, $Z_{32d} = Z_{12d}$
J inverter	$Z_{c01} = Z_{c34} = 62.7$ $Z_{c12} = Z_{c23} = 65.8$	$Z_1 = Z_4 = 125.4$ $Z_{z1} = 149.6, Z_{z2} = 125.3$
J inverter (θ)	$\theta_{01} = \theta_{12} = \theta_{23} = \theta_{34} = 90^\circ$	$\theta_1 = \theta_4 = 30^\circ$
Others	$C_1 = C_4 = 2.20\,\text{pF}$, $C_2 = C_3 = 2.42\,\text{pF}$	

All the frequencies are in central frequency f_0.

Based on the synthesis above, a 3rd-order ICDBR filter is designed (shown in Fig. 5). For comparison, a classical one with the same order is designed as well. Both filters are designed at 1 GHz, with 4% relative bandwidth. As the interdigital capacitor [19, 20] is not absolutely equal to capacitance, the impedances of open-circuited stubs need to be tuned slightly. Table 1 summarizes the final parameters of classical and ICDBR filters. The LF transmission zeros are set at 0.8 and 0.88 GHz, and the HF transmission zeros are set at 1.12 and 1.2 GHz. The comparison to the classical one is shown in Fig. 6 (simulation in ADS Momentum), which shows that the bandwidth is kept, with a shift of transmission zeros caused by the dual-line equivalent circuit. Fig. 6 also shows that ICDBR has a high spurious responses suppression at both low and high frequencies. The transmission zeros F_{z1}, F_{z2} are provided by open-circuited stubs of the π-network, and the Z_{z1}, Z_{z2} parameters are optimized in order to control the position of new transmission zeros. The electrical length of stubs $\theta_{ij} = \theta'_{ij} + \theta_{ijd}$.

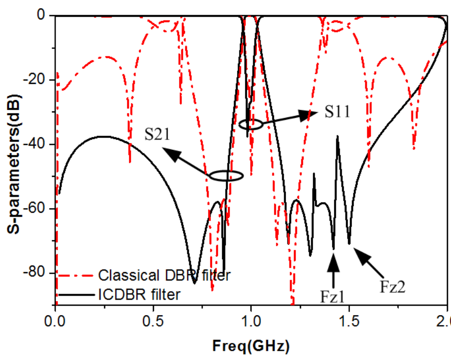

Figure 6. The S-parameters of the compact DBR filter (ICDBR) and classical one.

3. FABRICATION AND MEASUREMENT

To validate the concept and demonstrate the contribution of this new synthesis, a 3rd-order compact ICDBR filter was fabricated on PTFE with a dielectric constant of 2.65 and a thickness of 1 mm substrate. The measured central frequency was set to 1 GHz and fractional bandwidth to 4%. The layout model and partial parameters are given in Fig. 7, which has an area of $0.24 * 0.39\lambda_0^2$. The miniaturization percentage in comparison to the classical DBR filter $(0.55 * 1.01\lambda_0^2)$ is 83%. A photo of the fabricated compact ICDBR filter is shown in Fig. 8, and the measurement was carried out from 50 MHz to 2 GHz

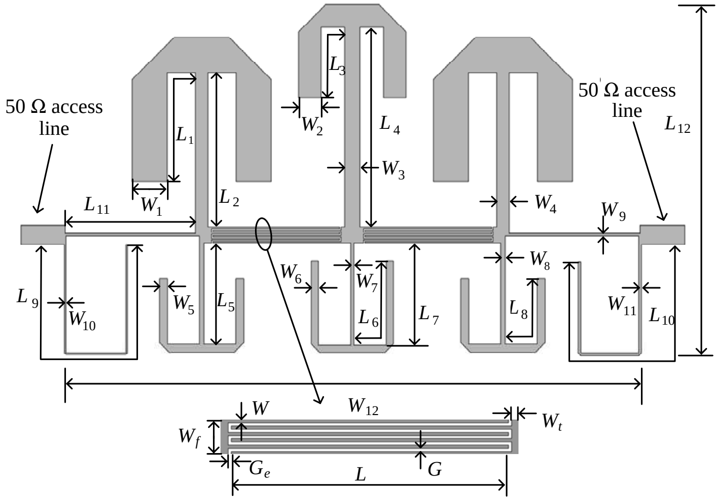

Figure 7. The layout model and final parameters of the ICDBR filter ($W = 0.2$, $G = 0.2$, $G_e = 0.2$, $W_t = 0.5$, $W_f = 2.2$, $L = 17.5$, $W_1 = 4.84$, $W_2 = 3.10$, $W_3 = 2.11$, $W_4 = 1.73$, $W_5 = 1.11$, $W_6 = 0.98$, $W_7 = 0.43$, $W_8 = 0.63$, $W_9 = 0.37$, $W_{10} = 0.20$, $W_{11} = 0.37$, $W_{12} = 79.7$, $L_1 = 19.3$, $L_2 = 24.4$, $L_3 = 16.7$, $L_4 = 24.1$, $L_5 = 14.5$, $L_6 = 14.5$, $L_7 = 16.2$, $L_8 = 14.5$, $L_9 = 38.8$, $L_{10} = 35.8$, $L_{11} = 17.9$, $L_{12} = 48.4$, all units are in mm).

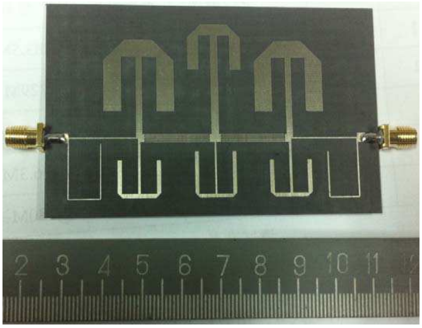

Figure 8. The photo of the ICDBR filter.

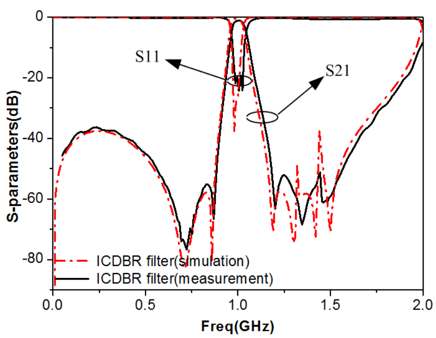

Figure 9. The simulation and measurement results of the ICDBR filter.

using the Agilent 8719ES Vector Network Analyzer. Simulation and measurement results are shown in Fig. 9, which show good agreement. The measured insertion loss is about 1.3 dB with a SMA connector, with a shift of transmission zeros at high frequencies, which was mainly attributed to the tolerances of the fabrication process. Finally, Table 2 compares the proposed filter with some recent state-of-the-art designs. It is summarized that this presented filter has the best suppression of spurious response in LF band, high miniaturization level and reasonably low passband *IL*.

Table 2. Comparisons of measured results for reported compact DBR filter with suppression of suppression of spurious responses.

Ref.	Central Frequency (GHz)	RL FBW	Order	Insertion loss (dB) classical/proposed	LF stopband (GHz) with 35 dB rejection	HF stopband (GHz) with 35 dB rejection	ε_r h (mm)	Lumped elements (numbers)	Size reduction	Employed technology
MTT [15] 2006	5 GHz	4.5%	4	−2.97/−3.1 dB	0~0.37f_0 0.43~0.86f_0	1.14~1.8f_0	9.9 0.254	N/A	N/A	capacitive-coupling
MWCL [12] 2006	5 GHz	5%	3	−1.46/−1.83 dB	N/A	1.24~2.7f_0	9.9 0.254	N/A	N/A	Lowpass L-C-L
MWSYM [9] 2008	1 GHz	≈ 18%	1	−0.39/−0.57 dB	N/A	N/A	3.38 0.813	Capacitor (2)	75%	Lumped element
		4%		−1.75/−2.56 dB						
MOT [11] 2011	1 GHz	≈ 18%	1	−0.39/−0.44 dB	N/A	N/A	3.38 0.813	Capacitor (2)	70%	Lumped elements
		4%		−1.75/−1.98 dB						
APMC [10] 2011	1 GHz	18%	2	−0.43/−0.7 dB	N/A	2~4f_0	3.38 0.813	Capacitor (7)	95%	Lumped elements and Lowpass L -C-L
		4%		−1.93/3.15 dB						
This work	1 GHz	4%	3	−1.1/−1.3 dB	0~0.88f_0	1.12~1.72f_0	2.65 1.0	N/A	83%	π-network and capacitive inverter

4. CONCLUSION

This paper proposed a compact DBR filter (ICDBR) with high spurious responses suppression by replacing a J inverter with two kinds of equivalent topologies and using the dual-line equivalent circuit of open-circuited stubs. The proposed ICDBR filter achieves a great miniaturization 83% in comparison to the classical one. The new structure uses interdigital capacitor coupling to suppress spurious responses at low frequencies and introduces another two transmission zeros by open-circuited stubs so as to increase rejection at high frequencies. The relevant equations are given in the paper. Theoretical analysis is presented, and the feasibility of the approach has been experimentally verified with microstrip circuit prototypes. The simulation and measurement results are in good agreement.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China (NSFC) under Project No. 61271017 and the research fund of ZTE corporation.

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