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A Compact Wideband Bandpass Filter Using a Coupled-Line Quad-Mode Resonator

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Abstract—A novel, compact wideband bandpass filter based on an improved quad-mode resonator is proposed in this paper. Due to the usage of a coupled-line section, the resonator has a quad-mode behavior. The resonant frequencies can be tuned by regulating not only the electrical lengths, but also the characteristic impedances. Owing to the symmetry of the construction, even- and odd-mode analysis is utilized to analyze the proposed resonator. Finally, a wideband bandpass filter with 88% (2.1 to 5.4 GHz) relative bandwidth is designed, fabricated, and measured. The measured results are in good agreement with the simulated ones, which demonstrates the feasibility of the design approach.

1. INTRODUCTION

Wideband bandpass filters play an increasingly important role in the rapid developing wireless communication, and the pros and cons of their performance directly affect the quality of the whole system of communication. Thus, more and more attention has been paid to filters of this type. Recently, many kinds of structures and bandwidth expanding technology have been investigated [1–6]. For instance, a filter including four short-circuited stubs is exhibited in [1]. This filter is designed by cross coupling between the first and the last short-circuited stubs to realize high selectivity. However, it leads to a large circuit area. In [2], the bandpass filter uses composite short- and open-circuited stubs to achieve sharpened rejection slopes near the two cutoff edges of the passband, but the size is larger. In [3], a low-loss wideband filter employing a transversal resonator with a ground via is presented. This resonator displays an additional resonant mode compared with its non-grounded counterpart, but the circuit area is not compact. In addition, some filters using multiple-mode resonators have been proposed in [7–16]. In short, high performance and miniaturization have become an inevitable trend.

In this paper, we propose another type of wideband bandpass filter employing a quad-mode resonator, wherein the resonator consists of two pairs of coupled lines. Thus, it can realize a compact size, but the multimode performance remains constant. Owing to the coupled line instead of the transmission line, a resonator displays an extra resonant mode compared with [3], and the resonant frequencies can be adjusted easily by changing the electrical lengths and the characteristic impedances. Thus, the bandwidth of the filter can be tuned flexibly. Detailed theoretical design, simulation, and experimental results of the wideband filter are discussed and demonstrated. In addition, the measured results of the proposed filter are consistent with the full-wave simulation results.

2. THE PROPOSED CIRCUIT AND DESIGN APPROACH

The circuit configuration of the modified resonator is displayed in Figure 1(a). Since the structure is symmetrical, the even- and odd-mode equivalent circuits [17] are shown in Figure 1(b) and Figure 1(c).

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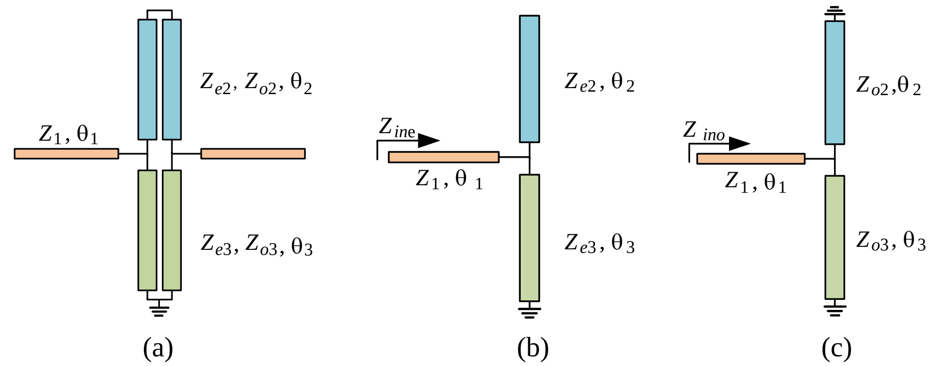

Figure 1. (a) Circuit configuration of the modified resonator. (b) Even-mode equivalent circuit. (c) Odd-mode equivalent circuit.

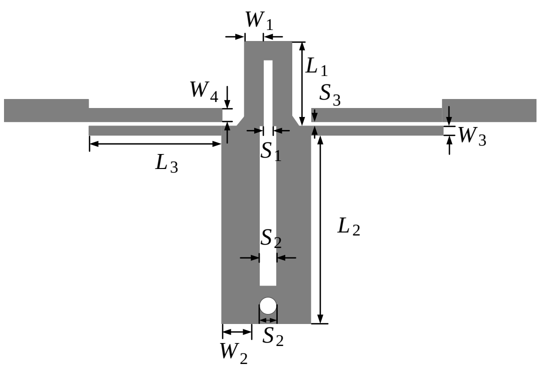

Figure 2. Layout of the proposed filter.

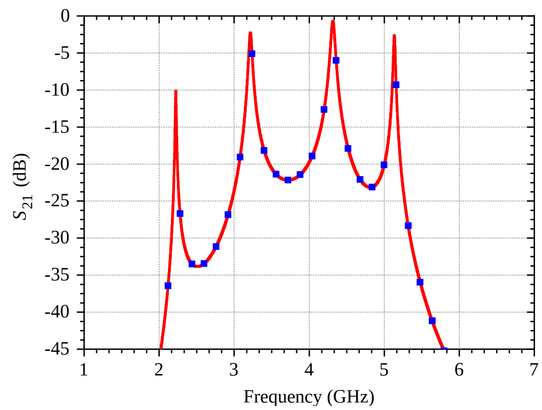

Figure 3. Full-wave simulated result of the proposed resonator.

The characteristic impedance of the transmission line is Z_1, and the corresponding electrical length is θ_1. The even- and odd-mode characteristic impedances of the coupled lines are defined as Z_{e2}, Z_{e3}, Z_{o2}, and Z_{o3}, respectively. The corresponding electrical lengths are θ_2 and θ_3. Figure 2 shows the layout of the proposed filter, and the physical dimensions are (units: mm): $W_1 = 0.75$, $S_1 = 0.45$, $L_1 = 5.5$, $W_2 = 5$, $S_2 = 1.5$, $L_2 = 16$, $W_3 = 0.18$, $W_4 = 0.5$, $L_3 = 13.8$. The ports are weakly coupled [18] with $S_3 = 1.7$ mm and the resonant frequencies can be obtained from the full-wave simulated results. As is exhibited in Figure 3, the resonant frequencies are equal to 2.222 GHz, 3.216 GHz, 4.318 GHz and 5.135 GHz, respectively.

Based on the analysis theory [19], the even-mode input impedance can be expressed as

$$Z_{ine} = \frac{Z_1 Z_{e2} Z_{e3} \tan\theta_3 - Z_1^2 \tan\theta_1 \left(Z_{e3} \tan\theta_2 \tan\theta_3 - Z_{e2}\right)}{j\left(Z_{e2} Z_{e3} \tan\theta_1 \tan\theta_3 + Z_1 Z_{e3} \tan\theta_2 \tan\theta_3 - Z_1 Z_{e2}\right)} \tag{1}$$

The odd-mode input impedance can be expressed as

$$Z_{ino} = Z_1 \frac{\left(-Z_1 Z_{o2} \tan\theta_1 \tan\theta_2 - Z_1 Z_{o3} \tan\theta_1 \tan\theta_3 - Z_{o2} Z_{o3} \tan\theta_2 \tan\theta_3\right)}{j\left(Z_1 Z_{o2} \tan\theta_2 + Z_1 Z_{o3} \tan\theta_3 - Z_{o2} Z_{o3} \tan\theta_1 \tan\theta_2 \tan\theta_3\right)} \tag{2}$$

Based on the resonant condition, the even- and odd-mode input admittances should be equal to zero at the resonant frequencies [20]. Consequently, the even- and odd-mode resonant equations can be derived as

$$Z_{e2} Z_{e3} \tan\theta_1 \tan\theta_3 + Z_1 Z_{e3} \tan\theta_2 \tan\theta_3 - Z_1 Z_{e2} = 0 \tag{3}$$

$$Z_1 Z_{o2} \tan\theta_2 + Z_1 Z_{o3} \tan\theta_3 - Z_{o2} Z_{o3} \tan\theta_1 \tan\theta_2 \tan\theta_3 = 0 \tag{4}$$

According to the relationship between electrical length and frequency [7], the Equations (3) and (4) can be further expressed as

$$Z_{e2}Z_{e3}\tan\left(\frac{\theta_1 f}{f_0}\right)\tan\left(\frac{\theta_3 f}{f_0}\right)+Z_1Z_{e3}\tan\left(\frac{\theta_2 f}{f_0}\right)\tan\left(\frac{\theta_3 f}{f_0}\right)-Z_1Z_{e2}=0 \tag{5}$$

$$Z_1Z_{o2}\tan\left(\frac{\theta_2 f}{f_0}\right)+Z_1Z_{o3}\tan\left(\frac{\theta_3 f}{f_0}\right)-Z_{o2}Z_{o3}\tan\left(\frac{\theta_1 f}{f_0}\right)\tan\left(\frac{\theta_2 f}{f_0}\right)\tan\left(\frac{\theta_3 f}{f_0}\right)=0 \tag{6}$$

As can be deduced from expressions (5) and (6), the resonant frequencies can be tuned by regulating not only the electrical lengths but also the characteristic impedances. Namely, the resonant frequencies of the even mode can be adjusted by the characteristic impedances Z_1, Z_{e2}, and Z_{e3}, but the resonant frequencies of the odd mode are mainly affected by the characteristic impedances Z_1, Z_{o2}, and Z_{o3}.

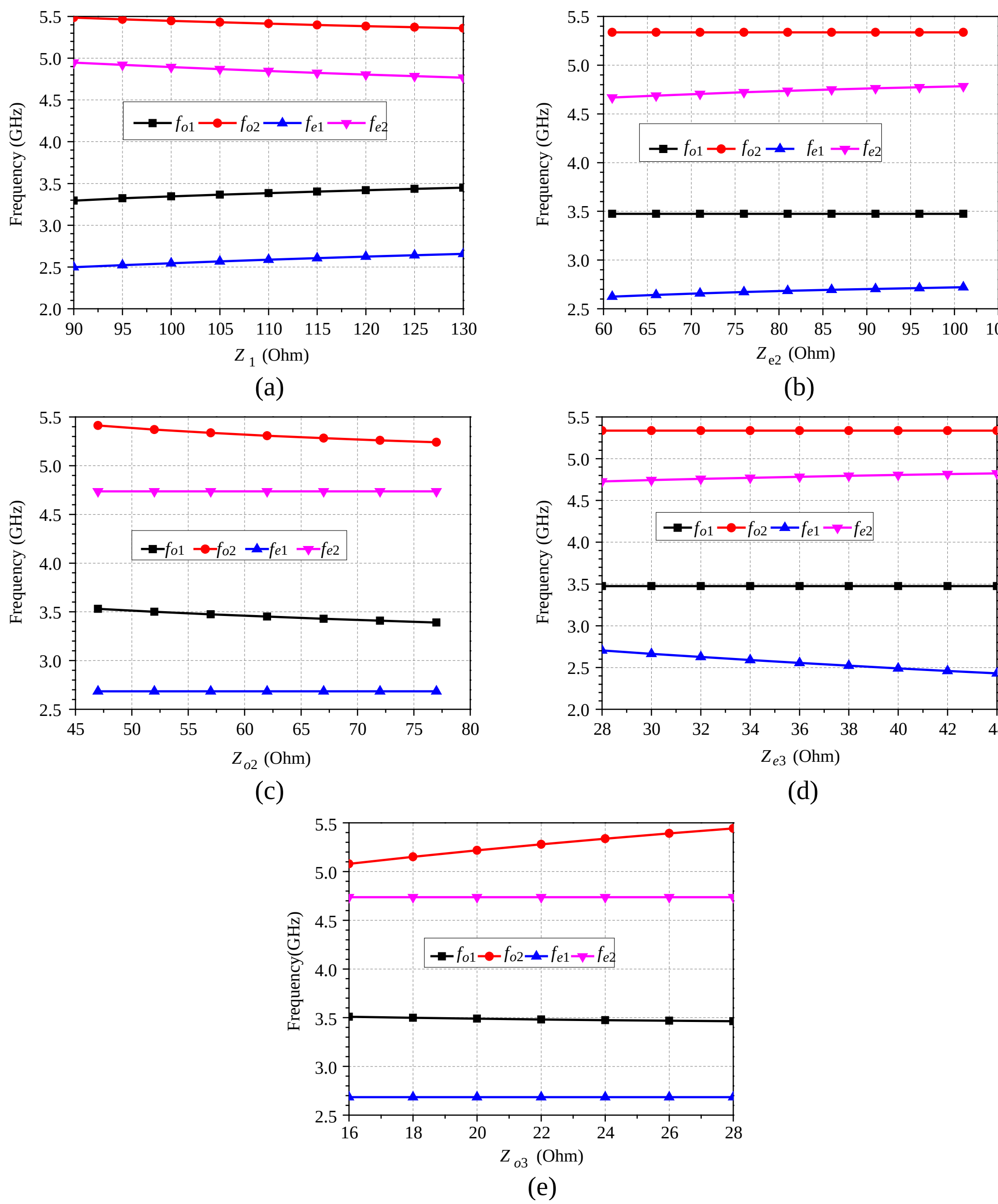

Figure 4. The influence of characteristic impedances on resonant frequencies under (a) Z_1, (b) Z_{e2}, (c) Z_{o2}, (d) Z_{e3}, and (e) Z_{o3}.

In order to make clear of the effect of characteristic impedances (Z_1, Z_{e2}, Z_{o2} Z_{e3} and Z_{o3}) on resonant frequencies, the original parameters are defined as follows: $Z_1 = 139\,\Omega$, $\theta_1 = 45°$, $Z_{e2} = 81\,\Omega$, $Z_{o2} = 57\,\Omega$, $\theta_2 = 19°$, $Z_{e3} = 29\,\Omega$, $Z_{o3} = 24\,\Omega$, $\theta_3 = 46°$. Then one of the characteristic impedances is varied while others remain constant. The resonant frequencies versus characteristic impedances are illustrated in Figure 4. It can be observed that f_{o1} and f_{e1} increase but f_{o2} and f_{e2} decrease when Z_1 changes from 90 to 130 Ω in Figure 4(a). This indicates that the bandwidth of the filter decreases with the increasing of Z_1. As denoted in Figures 4(b) and (d), f_{e1} and f_{e2} change but f_{o1} and f_{o2} remain constant when Z_{e2} and Z_{e3} vary. When Z_{e2} increases, both f_{e1} and f_{e2} increase. When Z_{e3} increases, f_{e2} increases but f_{e1} decreases. Figures 4(c) and (e) show that f_{o1} and f_{o2} alter but f_{e1} and f_{e2} are fixed when Z_{o2} and Z_{o3} change. This indicates that the odd-mode characteristic impedances only have an influence on the odd-mode resonant frequencies, and the even-mode characteristic impedances only produce effects on even-mode resonant frequencies. Besides, when Z_{e3} and Z_{o3} increase, the bandwidth of the filter increases. But the bandwidth of the filter decreases with the rising of Z_1, Z_{e2} and Z_{o2}. According to the principle, different wideband bandpass filters can be fabricated. For convenient applications, the design procedure for this proposed filter can be summarized as follows:

Step 1) Based on the resonant condition, the even- and odd-mode resonant equations can be derived.

Step 2) According to the requirement, the characteristic impedances (Z_1, Z_{e2}, Z_{o2}, Z_{e3}, Z_{o3}) and the corresponding electrical lengths (θ_1, θ_2, θ_3) are determined adequately. Based on the design equations, the resonant frequencies can be calculated.

Step 3) Convert all the electrical parameters into the physical dimensions, then the layout of the proposed structure with physical dimensions can be simulated by using simulations tools such as Advanced Design System (ADS) and high-frequency structure simulator (HFSS). Then the resonant frequencies can be obtained.

Step 4) Check whether the resonant frequencies obtained by steps 2) and 3) are consistent. If yes, then progress to the next step. Otherwise, the resonant condition can't be realized by the proposed approach.

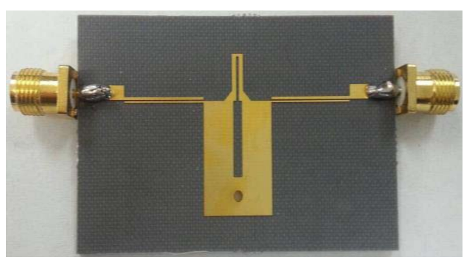

Figure 5. Photograph of the fabricated filter.

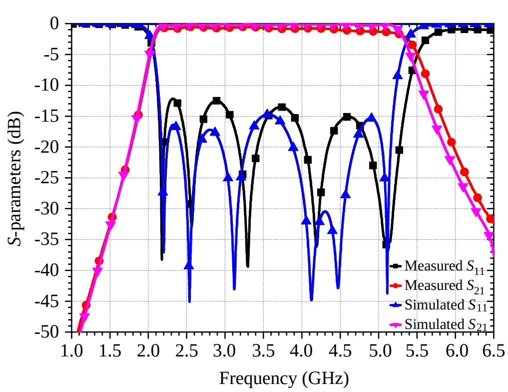

Figure 6. Simulated and measured results of the proposed filter.

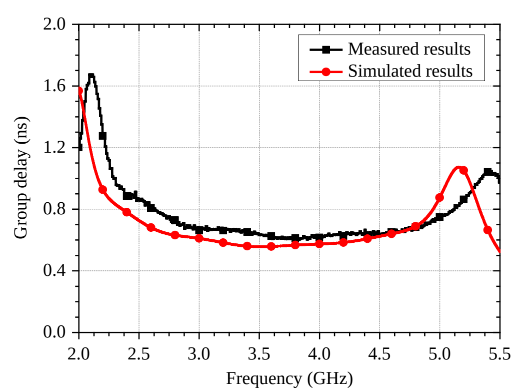

Figure 7. Simulated and measured group delays.

Table 1. Performance comparison of this proposed filter with the previous ones.

Ref.	3-dB FBW (%)	Group delay variation (ns)	Transmission poles (in-band)	Size ($\lambda_g \times \lambda_g$)	Center frequency (GHz)
[3]	83.5%	< 0.72	5	0.29×0.19	4
[6]	48.2%	< 0.8	5	0.68×0.53	3
	61.7%	< 0.7	5	0.68×0.45	3
[9]	60%	< 0.8	5	0.72×0.16	5.3
[10]	72.6%	< 0.7	4	0.5×0.26	6
This work	**88%**	$\mathbf{< 0.62}$	**6**	$\mathbf{0.7 \times 0.38}$	**3.8**

Step 5) Tune the value of S_3. When the ports are weakly coupled, the proposed filter can be simulated by using high-frequency structure simulator (HFSS). Finally, the proposed filter is manufactured and measured.

3. MICROSTRIP EXAMPLE

In this section, the proposed filter is designed, manufactured and measured. Figure 5 shows a photograph of the filter, which is fabricated on F4B with $\varepsilon_r = 2.45$ and $h = 1$ mm. According to Figure 2, the physical dimensions are given as follows (units: mm): $W_1 = 0.75$, $S_1 = 0.45$, $L_1 = 5.5$, $W_2 = 5$, $S_2 = 1.5$, $L_2 = 16$, $W_3 = 0.18$, $W_4 = 0.5$, $S_3 = 0.18$, $L_3 = 13.8$.

Figure 6 presents the measured and simulated results. An excellent agreement can be observed between the measured and simulated results. The insertion loss is less than 1.5 dB, whilst the return loss is greater than 12.2 dB. The measured 3-dB bandwidth of this filter is almost 88% (from 2.1 to 5.4 GHz). The simulated and measured group delays are displayed in Figure 7. It can be seen that the measured group delay varies from 1.04 to 1.66 ns in the entire passband with a maximum variation of 0.62 ns. To further demonstrate the performance of the filter, Table 1 compares some prior bandpass filters with this work. It is apparent that the proposed filter has a better performance than the other filters.

4. CONCLUSIONS

In this work, a bandpass filter employing a novel quad-mode resonator is proposed. This design utilizes the resonator to realize a wide passband, resulting in compact size. The resonant frequencies can be tuned by regulating not only the electrical lengths but also the characteristic impedances. A detailed description of the design approach is given, and an implemented filter with 88% (2.1 to 5.4 GHz) relative bandwidth is presented for validation. The good agreement between the measured and simulated results demonstrates the feasibility of the design technique.

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