Design of a Compact Triple-Mode Dielectric Resonator BPF with Wide Spurious-Free Performance

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SUMMARY A novel compact 5-pole bandpass filter (BPF) using two different types of resonators, one is coaxial TEM-mode resonator and the other dielectric triple-mode resonator, is proposed in this paper. The coaxial resonator is a simple single-mode resonator, while the triple-mode dielectric resonator (DR) includes one TM01δ mode and two degenerate HE11 modes. An excellent spurious performance of the BPF is obtained due to the different resonant behaviors of these two types of resonators used in the BPF. The coupling scheme of the 5-pole BPF includes two cascade triplets (CTs) which produce two transmission zeros (TZs) and a sharp skirt of the passband. Behaviors of the resonances, the inter-resonance couplings, as well as their tuning methods are investigated in detail. A procedure of mapping the coupling matrix of the BPF to its physical dimensions is developed, and an optimization of these physical dimensions is implemented to achieve best performance of the filter. The designed BPF is operated at 1.84 GHz with a bandwidth of 51 MHz. The stopband rejection is better than 20 dB up to 9.7 GHz (about 5.39× frequency). Good agreement between the designed and theoretically synthesized responses of the BPF is reached, verifying well the proposed configuration of the BPF and its design method.

key words: Bandpass filter (BPF), dielectric resonator (DR), triple-mode, spurious performance, transmission zeros (TZs).

1. Introduction

Dielectric resonators (DRs) have many distinctive features, like low loss, small size, light weight, and temperature-stable property, and bandpass filters (BPFs) using DRs are attractive for many RF front-end systems because of their high-performance realizable by taking advantage of the DRs [1]-[2].

Since it was shown that DRs can be used to develop compact and high-Q BPFs in 1968 [3][4], various works on DR BPFs have been carried out [5]-[13]. At first, DRs using TE01δ mode [4]-[9] and TM01δ mode [10]-[13] were widely used because these single mode DRs were relatively simple in configuring and designing BPFs. Later, to further reduce the size and weight of BPFs for advanced communication systems, various BPFs employing dual-mode DRs were proposed [14]-[19]. Dual HE11-mode DR loaded cavity BPFs was reported in 1982, yielding a considerable size reduction [14]. Dual TM11-mode DR BPFs were proposed in [15], in which the TM11-like degenerate modes were designed as the lowest modes in the conductor-loaded DRs. However, the conductor loaded on DRs introduced extra ohmic losses. Dual TE01δ-modes in cross-shaped DRs were presented in [17], but the inline topology of the BPF was difficult to introduce transmission zeros (TZs) to improve its frequency selectivity. A novel compact TM11 dual-mode DR filter was proposed in [18] using planar coupling configuration which was flexible in producing multiple TZs.

In recent years, BPFs using triple-mode DRs have been receiving significant attentions due to their attractive potentials in future wireless communication applications requiring smaller size, lighter weight, and lower loss [20]-[30]. A TE01δ triple-mode BPF was developed in [20] using cubic DRs. In [26], a triple-mode DR using one TM01δ mode and two HE11 degenerate modes was designed to develop miniaturized BPFs. [29] tried to design triple-mode DR BPFs with controllable TZs. The novel triple-mode DR was designed off-centered in a metal cylinder, which was quite difficult in the assembling and tuning of the BPF. The spurious characteristics of this BPF was also not favorable. A DR BPF with improved spurious performance was reported in [30], using a triple-mode cube DR and two single mode DR slabs. The unwanted spurious resonances were suppressed by the dissimilar higher-order modes in these two different types of DRs. However, it is quite difficult to realize controllable couplings in the design of the BPF. In this paper, a novel compact 5-pole BPF with combined use of two coaxial resonators and one triple-mode DR is proposed to realize simultaneously volume reduction and excellent spurious performance. Detailed descriptions of the resonances and inter-resonance coupling scheme of the BPF are given in Sec. 2. A precise design method is described and demonstrated by a design example of a 5-pole BPF in Sec. 3. A good agreement is observed between the electromagnetic (EM) simulated response of the BPF and the desired target specifications.

2. The Proposed Triple-Mode DR and BPF

The configuration of the proposed triple-mode DR is shown in Fig. 1. A DR rod is mounted inside a cylindrical metal cavity with a height of h, and a radius of r, and is short-circuited on the bottom wall of the cavity. The DR has a dielectric constant of 45.0 and a loss tangent of 5.0 × 10⁻³. The metal of the cavity is copper with a conductivity of 5.8
The cavity size is determined as \( h_c = 13 \text{ mm} \) and \( r_c = 19 \text{ mm} \).

FIG. 1 Configuration of the proposed triple-mode DR. (a) Top view and (b) side view.

### 2.1 Resonance Behaviors in the Triple-Mode DR

Resonance behaviors in the above-described triple-mode DR is investigated by using the commercially available electromagnetic simulator, HFSS Eigenmode solver. Fig. 2 shows the magnetic field distributions (\( H \)-field) of the first three resonances in the DR. It is observed that the TM\(_{01\delta}\) mode is circularly polarized (i.e., the orientation of the field vector is rounding a circle), while the two degenerate HE\(_{11}\) modes are linearly polarized. Hereafter, the horizontally polarized HE\(_{11}\) mode is defined as HE\(_{11}^+\) mode, while the vertically polarized as HE\(_{11}^-\) mode. It is apparent that these three resonant modes are orthogonal to each other.

FIG. 2 Magnetic field distributions of the triple-mode resonator. Perspective view of (a) TM\(_{01\delta}\), (b) HE\(_{11}^+\), and (c) HE\(_{11}^-\). Top view of (d) TM\(_{01\delta}\), (e) HE\(_{11}^+\), and (f) HE\(_{11}^-\). Side view of (g) TM\(_{01\delta}\), (h) HE\(_{11}^+\), and (i) HE\(_{11}^-\).

Fig.3(a) and (b) show the variations of the resonant frequencies and unloaded \( Q \)-factor \( Q_u \) of the triple modes versus the height \( h_d \) of the DR with a radius of \( r_d = 14.5 \text{ mm} \). It is seen that with the increase of \( h_d \), the resonant frequency of TM\(_{01\delta}\) mode reduces quickly, whereas those of the two HE\(_{11}\) modes decrease slowly. The \( Q_u \) values of all the three modes vary little versus \( h_d \). It is worth noting that when \( h_d = 11.15 \text{ mm} \), the resonant frequencies of all the three modes are equal.

FIG. 3 Variations of (a) the resonant frequencies and (b) the \( Q_u \) values, versus the height \( h_d \) of the proposed DR with a radius of \( r_d = 14.5 \text{ mm} \).

### 2.2 Configuration and Coupling Scheme of the BPF

The configuration of the proposed 5-pole BPF is shown in Fig. 4(a) in which, Cavity I and III are coaxial TEM single-mode resonators, while Cavity II is the dielectric-loaded triple-mode resonator.

A generally considered coupling scheme of this 5-pole BPF is given in Fig. 4(b), where the TEM mode in Cavity I couples to all the three modes in Cavity II, and the same is true for Cavity III. Here in Fig. 4(b), \( S \) and \( L \) denote input and output ports, respectively, Nodes 1 and 5 represent two TEM modes in the coaxial Cavity I and III, Nodes 2, 3, and 4 stand for modes HE\(_{11}^-\), TM\(_{01\delta}\), and HE\(_{11}^+\) in Cavity II, respectively.

However, a careful observation of the magnetic field in the Cavities, as shown in Fig. 4(a), suggests that the vertical \( H \)-field component of the TEM mode in Cavity I (Node 1) has a very weak coupling with the HE\(_{11}^+\) mode in Cavity II (Node 4) because near the coupling area A shown in Fig. 4(a), the HE\(_{11}^+\) mode has almost zero vertical \( H \)-field component. The same consideration can also be applied to the TEM mode in Cavity III (Node 5) and the HE\(_{11}^-\) mode in Cavity II (Node 2).

Therefore, the cross-coupling between Node 1 and 4 and the cross-coupling between Node 5 and 2 can be ignored.
Determine the physical dimensions of the BPF and above-obtained coupling matrix structures and inter-couplings between cavities, based on the Then adjust the resonant frequencies, design the I/O values, by using an electromagnetic simulator (e.g., HFSS).

(2) Design the appropriate DR cavity according to the matrix, as well as the synthesized ideal response of the filter.

(3) Determine the configuration of the proposed 5-pole BPF. (b) Coupling scheme of the BPF. (c) Simplified coupling scheme of the BPF.

Flowchart of the design of our BPF is given in Fig. 5. The design procedures are summarized into the following steps:

(1) Determine the minimum number of reflection poles and TZs of the BPF based on the design specifications. Choose the coupling scheme of the BPF, and calculate its coupling-matrix, as well as the synthesized ideal response of the filter.

(2) Design the appropriate DR cavity according to the required cavity size, resonant frequencies, and unloaded $Q_u$ values, by using an electromagnetic simulator (e.g., HFSS). Then adjust the resonant frequencies, design the I/O structures and inter-couplings between cavities, based on the above-obtained coupling-matrix.

(3) Determine the physical dimensions of the BPF and simulate its S-parameters by using HFSS. Extract the corresponding coupling-matrix of the BPF from the simulated S-parameters and compare the extracted coupling-matrix with the synthesized coupling-matrix obtained in Step (1).

(4) Exam and minimize the deviation of each element of the extracted coupling-matrix from the ideal one by tuning the corresponding physical dimensions of the BPF until the return loss ($R.L.$) is larger than 15 dB over the whole passband.

In this paper, the 5-pole BPF to be design is centered at 1.84 GHz and has a passband bandwidth of 50 MHz. The passband return loss is better than 20 dB. Two transmission zeros at 1.88 and 1.90 GHz, both at the upper side of the passband, are to be designed. Of course, the design of TZs at other locations is also possible.

A synthesized ideal response of the BPF satisfying the above-described specifications is shown in Fig. 6(a). The coupling scheme of the BPF with two CT structures is illustrated again in Fig. 6(b), in which MC stands for magnetic coupling. The corresponding normalized coupling matrix of the BPF is given as follow [1]:

$$[M_I] = \begin{bmatrix} S & 1 & 2 & 3 & 4 & 5 & L \\ S & 0 & 1.01 & 0 & 0 & 0 & 0 \\ 1 & 1.01 & 0.04 & 0.78 & 0.39 & 0 & 0 \\ 2 & 0 & 0.78 & -0.5 & 0.55 & 0 & 0 \\ 3 & 0 & 0.39 & 0.55 & 0.13 & 0.60 & 0.24 \\ 4 & 0 & 0 & 0 & 0.60 & -0.29 & 0.83 \\ 5 & 0 & 0 & 0 & 0.24 & 0.83 & 0.04 \\ L & 0 & 0 & 0 & 0 & 0 & 1.01 \end{bmatrix}$$

From the obtained coupling matrix, we get the external
configuration and physical dimensions of the BPF is shown in Fig. 7(a) and 7(b). Below are detailed descriptions of the design of each part of the BPF.

### 3.1 Frequencies Tuning of the Triple-Mode DR

As shown in Fig. 7, a metal tuning screw located at the center of the DR in Cavity II is used to adjust its TM_{01δ} mode. Fig. 8(a) and 8(b) depict variations of the resonant frequencies and unloaded Q\textsubscript{u} values of the triple mode DR versus the height h\textsubscript{cs} of the center tuning screw. It is obvious that the resonant frequency of TM_{01δ} mode vary significantly with the change of h\textsubscript{cs} while those of the two HE\textsubscript{11} modes vary little. The Q\textsubscript{u} values of these three modes are not sensitive to the change of h\textsubscript{cs}. Thus, from Fig. 3(a) and 8(a), it is seen that by appropriately choosing h\textsubscript{cs} and h\textsubscript{h}, we can design TM_{01δ} and HE\textsubscript{11} modes at desired frequencies required by the design specifications.

### 3.2 Inter-Resonance Couplings

The inter-resonance couplings of the BPF, as shown by the coupling scheme in Fig. 6(b), are realized by employing two structures shown in Fig. 7(b): one is the inductive loop, and the other the coupling screw. The inductive loop between Cavity I and II are used to control m_{12} and m_{13}, while the loop between Cavity II and III to control m_{14} and m_{35}. Fig. 9 shows the variations of the coupling coefficients versus the height h\textsubscript{cs} of the inductive loop. It is observed that both m_{12} and m_{13} increase with h\textsubscript{cs} while other couplings vary slightly. On the other hand, two metal coupling screw-scircuited at the bottom of Cavity II as shown in Fig. 7(b), are
used to control the inner couplings $m_{23}$ and $m_{34}$ of triple-mode DR. Fig. 10 plots the variations of the coupling coefficients versus the height $h_{11}$ of the coupling screw. It is seen that the coupling coefficients $m_{23}$ and $m_{34}$ go up as $h_{11}$ become large, whereas other couplings keep almost unchanged. Therefore, the inter-resonance couplings can be controlled by choosing different combinations of $h_{11}$ and $h_{11}$ to meet the desired specifications.

3.3 Simulated Performance of the BPF

Finally, the input and output couplings of the BPF are simply implemented by using metal probes directly connected to central conductors of the coaxial Cavity I and III, and the desired external $Q_e$ values can be easily obtained by tuning the height of the feeding probes [2].

Following the above design procedures, the physical dimensions of the BPF in Fig. 7 are all determined. After several iterations of these dimensions in order to optimize the performance of the BPF, the finally obtained dimensions are shown in Fig. 7. The corresponding filter response by HFSS is compared in Fig. 11(a) with the one by the synthesized method. The EM simulated response shows that the designed BPF operates at 1.84 GHz with a bandwidth of 51 MHz, and the passband return loss is better than 15 dB. Two TZs located at 1.875 and 1.884 GHz are obtained. The deviations between the EM designed response and the synthesized one are considered mainly due to the fact that inter-resonance couplings $m_{12}$ and $m_{13}$ cannot be fully controlled only by the parameters $h_{11}$ and $h_{11}$, as shown in Fig. 9 and Fig. 10.

In Fig. 11(b), the simulated response of the BPF over a wide frequency range is illustrated. The HFSS simulation in Fig. 11(b) shows that the stopband rejection of the BPF is larger than 20 dB up to 9.7 GHz (about 5.39×$f_0$), except the point at 7.85 GHz. To verify the simulation results by HFSS, another well-known EM simulator, CST, is also used to simulate the designed BPF, and its simulation results are added in Fig. 11(b) in dotted lines. From the comparison in this figure, it is obvious that the simulation results by HFSS and CST agree quite well, which proves again our design method and results of the BPF.

4. Conclusion

A novel BPF with combined use of coaxial resonators and triple-mode DR is proposed in this paper. The filter takes advantage of the superior spurious-free performance of the coaxial resonator and the advantage of compact size of the triple-mode DR. The precise design method of a triple-mode DR BPF with a complicated coupling scheme is demonstrated by a 5-pole BPF with two CTs. The design includes the determination of the coupling matrix of the filter, and the mapping of the coupling matrix of the BPF to its physical dimensions. The EM simulated response of the
5-pole BPF proves the advantages of miniaturization, high selectivity, and excellent spurious performance of the proposed BPF. Good agreement between the EM designed results and the theoretically synthesized ones is obtained.

References