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Low-Loss Narrowband Filtering Switch Based on Coaxial Resonators

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ABSTRACT In this paper, a narrowband filtering switch with low loss and high selectivity is presented based on coaxial resonators for the first time. PIN diodes mounted on the printed circuit boards are embedded into a coaxial filter to enable ON and OFF states. In the ON-state, the PIN diodes are turned OFF, which do not introduce the loss and affect the linearity. Two transmission zeros are generated by a novel feeding structure, which improves the skirt selectivity. In the OFF-state, the PIN diodes are turned on. Then, lumped capacitors are loaded to the coaxial resonators so that the resonant frequencies of the resonators are changed. The passband at the operating frequency cannot be formed, resulting in high isolation. For demonstration, the coaxial-resonator-based filtering switch is designed and fabricated. Good agreement between simulated and measured results verifies the proposed ideas. Comparison with other reported filtering switches is given. The proposed filtering switch shows the advantages of high Q-factor, relatively compact size, and wide stopband responses, which is attractive in wireless systems.

INDEX TERMS Coaxial resonator, filtering switch, low loss, narrowband, high Q-factor, high skirt selectivity, transmission zeros.

I. INTRODUCTION

Filtering switches, which integrate two functions of the bandpass filter (BPF) [1]–[4] and the switch [5], [6], are attractive in many radio frequency systems, such as the time division duplex sub-system. In the last few years, lots of filtering switches have been proposed for loss/size reduction or isolation improvement. In [7]–[10], filtering switches are fabricated on printed circuit boards (PCBs) with high performance. For example, a microstrip filtering switch with quasi-elliptic bandpass responses is presented in [7] and it is utilized to construct a switchable diplexer. The lumped-element loaded resonators can be used to realize the miniaturized filtering switch in [11]. In addition, by using low-temperature co-fired ceramic (LTCC) technology, compact filtering switches is realized based on coupling control [12].

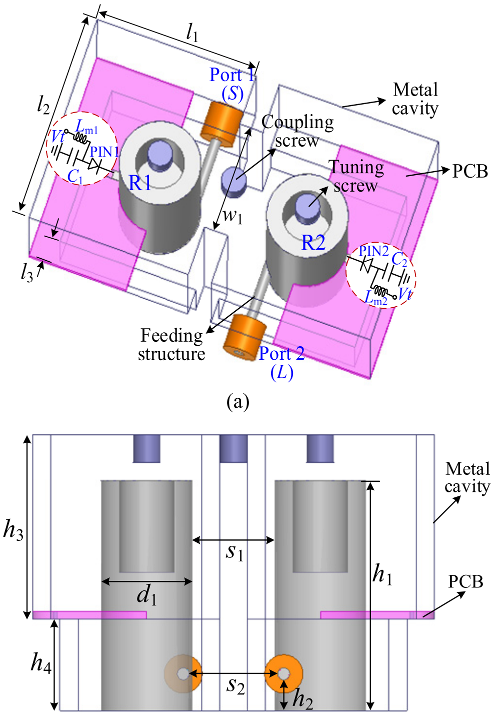
Due to low Q factors, if above filtering switches [7]–[12] are designed with narrow fractional bandwidth (FBW), *eg*, FBW less than 2%, their insertion losses would be very high. On the contrary, with high Q factors, cavity or dielectric resonators (DRs) are widely used in narrowband designs [13]–[18]. For instance, narrowband DR-based balun and balanced filters with good filtering responses are presented in [13] and [14]. A high-power and low-loss filtering switch can also be designed using DRs [15]. Nevertheless, its stopband is narrow because high order modes of the DR are closed to the passband. Moreover, the circuit size of the $TE_{11\delta}$-mode DR in [15] is large. As compared to the DRs, the coaxial resonators are easier to achieve a wider stopband and they are widely utilized in BPF designs [16]–[18]. However, to the author's knowledge, there are no reported filtering switches based on the coaxial resonators.

In this letter, a narrowband coaxial resonator filtering switch with low loss and high selectivity is proposed for the first time. The PIN diodes are connected to the coaxial resonators to switch on or off the passband. Since the PIN diodes are turned off in the ON-state, the loss is only introduced by the coaxial filter structure. Thus, the loss is lower than the overall loss of the cascaded BPF and switch. Transmission zeros (TZs) are introduced by a novel feeding structure. In the OFF-state, the loaded capacitors change the resonant frequencies of the coaxial resonators. Hence, signals cannot be transmitted in the passband frequency, realizing high isolation. The circuit is implemented and the experimental results are presented.

II. ANALYSIS OF THE COAXIAL-RESONATOR-BASED FILTERING SWITCH

A. CIRCUIT CONFIGURATION

The 3-D structure and front view of the proposed filtering switch are shown in Figs. 1(a) and (b), respectively. There are two short-circuited conductive posts (R1 and R2), two pieces of PCBs, two tuning screws, a coupling screw and the input/output feeding probes (S and L). The PCBs are embedded in the metal cavity. The switch circuitries, including the PIN diodes (PIN1 and PIN2), inductors (L_{m1} and L_{m2}) and capacitors (C_1 and C_2), are mounted on the PCBs and connected to the conductive posts. By controlling the PIN diodes, the proposed filtering switch works in the ON- and OFF-states.



(a)

(b)

FIGURE 1. Structure of the proposed filtering switch (a) 3-D view; (b) Front view.

B. ON-STATE OF THE FILTERING SWITCH

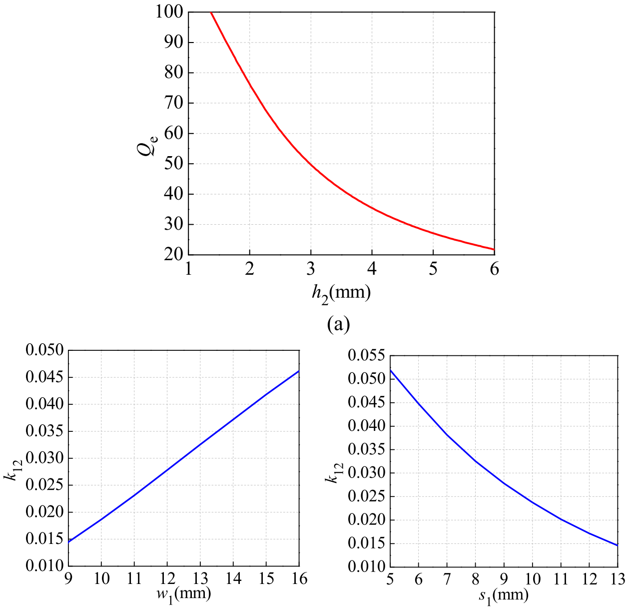
When PIN1 and PIN2 are turned off, the filtering switch is in the ON-state. Since no signals pass through the switch circuitries, the circuit in this state is the same as the conventional coaxial filter. And thus the filter design method can be applied.

Due to the use of the high-Q factor coaxial resonator, the proposed circuit can be designed with narrow FBW, eg, from 0.5% to 3%. As a design example, the desired passband is centered at $f_0 = 2.4$ GHz with the equi-ripple of 0.1 dB and the FBW is 2%. Based these required filtering responses, the lumped element values of the second-order prototype filter are selected as [19]: $g_0 = 1$, $g_1 = 0.8430$, $g_2 = 0.6220$, $g_3 = 1.3554$. The desired coupling coefficient k_{12} and external quality factor Q_{e} are calculated as [20]:

$$k_{12} = \frac{FBW}{\sqrt{g_1 g_2}} = 0.0276 \tag{1}$$

$$Q_e = \frac{g_0 g_1}{FBW} = 42.15 \tag{2}$$

In the circuit realization, the value of Q_{e} can be easy obtained by tuning the height of the feeding structures (h_2). Fig. 2(a) shows the simulated Q_{e} versus h_2. As can be seen, when h_2 increases, Q_{e} decreases. The required k_{12} can be achieved by controlling the size of the window (w_1) and the distance between two resonators (s_1). Figs. 2(b) and (c) show the extracted k_{12} against w_1 and s_1, respectively. It can be seen that the k_{12} increases as w_1 increases or s_1 decreases. With these parameters, the required filtering responses can be realized.



(a)

(b)

(c)

FIGURE 2. (a) Simulated Q_e versus h_2; (b) Simulated k_{12} versus w_1; (c) Simulated k_{12} versus s_1.

In order to enhance the skirt selectivity, the source-load coupling is introduced for generating TZs near the passband. Therefore, the filter topology in the ON-state can be shown as Fig. 3. Here, the source-load coupling (k_{SL}) can be realized by placing S and L closed to each other, as shown in Figs. 4(a) and (b). According to the filter design theories, it is noted that k_{12} and k_{SL} in this second-order filter topology should have different signs, namely, one is positive and the other is negative.

For the structure in Fig. 4(a), the input and output feeding structures are symmetrically placed, where the couplings

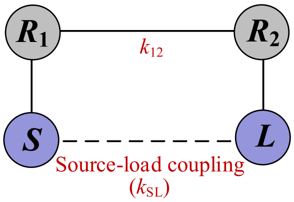
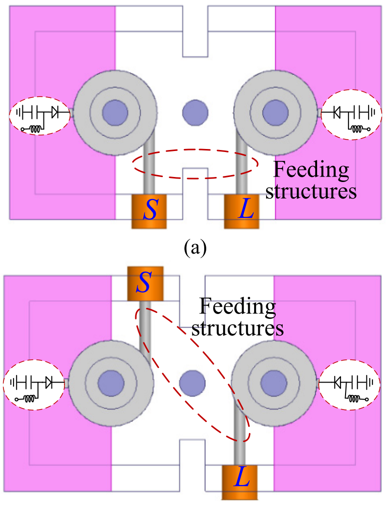


FIGURE 3. Topology of the filtering switch in the ON-state based on coaxial resonators.



(a)

(b)

FIGURE 4. Top view of the filtering switch with (a) symmetric feeding structures; (b) asymmetric feeding structures.

between R1 and R2 as well as between S and L are both magnetic coupling. Hence, k_{SL} and k_{12} have the same sign and there are no TZs. On the contrary, the input and output feeding structures in Fig. 4(b) are asymmetrically placed. Additional 180° phase difference from k_{SL} is realized. Thus, the requirement that k_{SL} and k_{12} should have different signs can be fulfilled. Simulated results of these two structures are shown in Fig. 5. As seen, two TZs can be generated by the asymmetric feeding structures in Fig. 4(b). Moreover, when s_2 decreases, the two TZs move closer to the passband, which enhance the skirt selectivity.

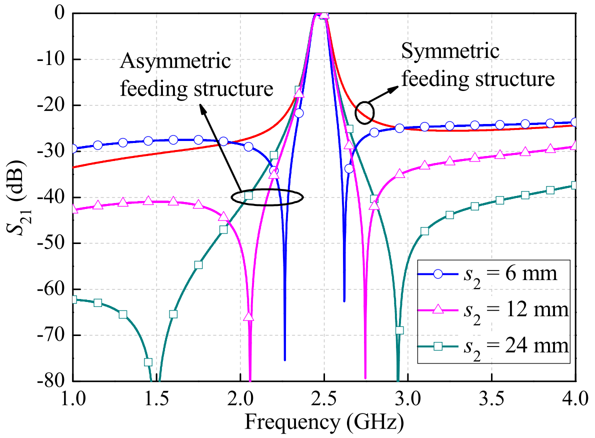
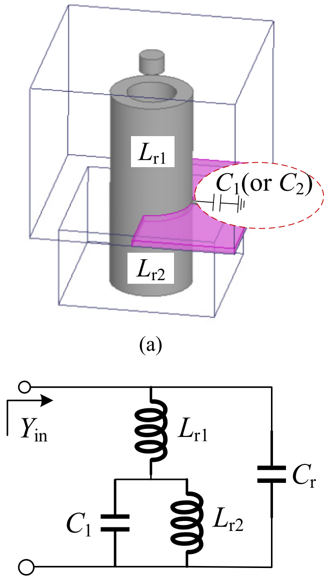


FIGURE 5. Simulated S_{21} with different distances between S and L (s_2).

C. OFF-STATE OF THE FILTERING SWITCH

When PIN1 and PIN2 are turned on, the filtering switch is in the OFF-state. C_1 and C_2 are loaded to the coaxial resonators. Fig. 6(a) shows the structure of the coaxial resonator loaded with C_1 or C_2. The corresponding equivalent LC circuit of the resonator in the OFF-state can be shown in Fig. 6(b), where C_r, L_{r1}, L_{r2} are the equivalent capacitor and inductors of the coaxial resonators. The input admittance can be calculated as

$$Y_{in} = j(\omega C_r - \frac{1-\omega^2 C_1 L_{r2}}{\omega(L_{r1}+L_{r2}-\omega^2 C_1 L_{r1} L_{r2})}). \tag{3}$$



(a)

(b)

FIGURE 6. Equivalent coaxial resonator in the OFF-state (a) 3-D structure; (b) LC lumped elements.

The resonance condition is $Y_{in} = 0$. From (3), it is known that the resonant frequencies of the resonators can be influenced by the loaded capacitors C_1 (or C_2). Fig. 7 shows the simulated S_{21} of the coaxial resonator under weak coupling. As seen, when C_1 (or C_2) increases, the resonant frequency decreases. In this case, when the PIN diodes are turned on, the resonant frequencies of the two resonators would be different from the passband frequency.

From the filter design theory, we know that the passband responses can be influenced by the resonant frequencies of the resonators. Thus, when the PIN1 and PIN2 are turned on, the values of C_1 and C_2 can be changed to adjust the responses of the filtering switch. Fig. 8 shows the simulated S_{21} of the filtering switch with different values of C_1 and C_2. As can be seen, by properly choosing the values of C_1 and C_2, eg, C_1 = 0.7 pF and C_2 = 1.1 pF, the in-band S_{21} is smaller

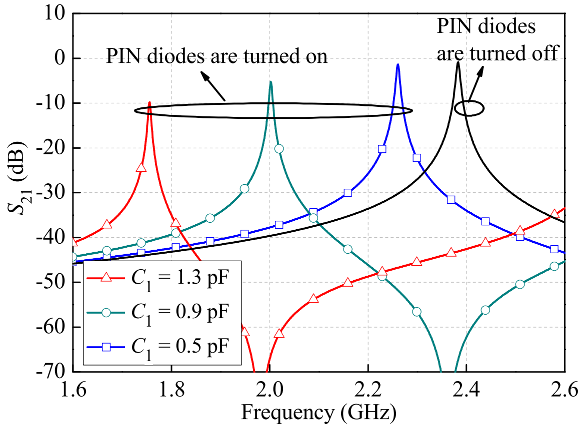


FIGURE 7. Simulated S_{21} of the coaxial resonator under weak coupling.

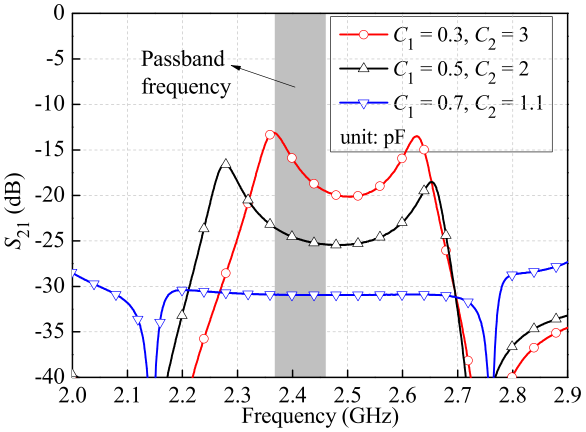


FIGURE 8. Simulated S_{21} of the filtering switch with different values of C_1 and C_2.

than −30 dB. High isolation is realized, which verifies the proposed ideas.

III. EXPERIMENT

For demonstration, the coaxial-resonator-based filtering switch is fabricated and measured. Its structure is shown in Fig. 1. The design parameters are given as follows (all in mm): $h_1 = 25$, $h_2 = 3.35$, $h_3 = 20$, $h_4 = 10$, $d_1 = 10$, $s_1 = 9$, $s_2 = 9.7$, $w_1 = 12$, $l_1 = 21.5$, $l_2 = 27$, $l_3 = 4$. The lumped elements of the switch circuitries are determined as: $C_1 = 0.7$ pF, $C_2 = 1.1$ pF, $L_\mathrm{m} = 56$ nH. And the diodes used in this design are implemented with Skyworks SMP 1345-079LF PIN diodes. The two pieces of PCBs have the thickness of 0.762 mm, dielectric constant of 2.55 and loss tangent of 0.0015. The photograph of the fabricated filtering switch is shown in Fig. 9. The filter housing with a size of $46 \times 27 \times 30$ mm^3 (or $0.368 \times 0.216 \times 0.24\lambda_g^3$) is made of aluminum.

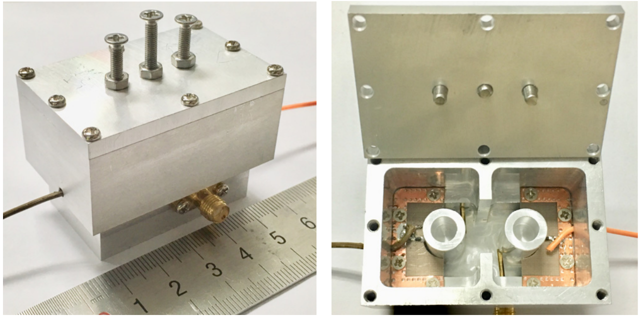


FIGURE 9. Photograph of the fabricated coaxial-resonator-based filtering switch.

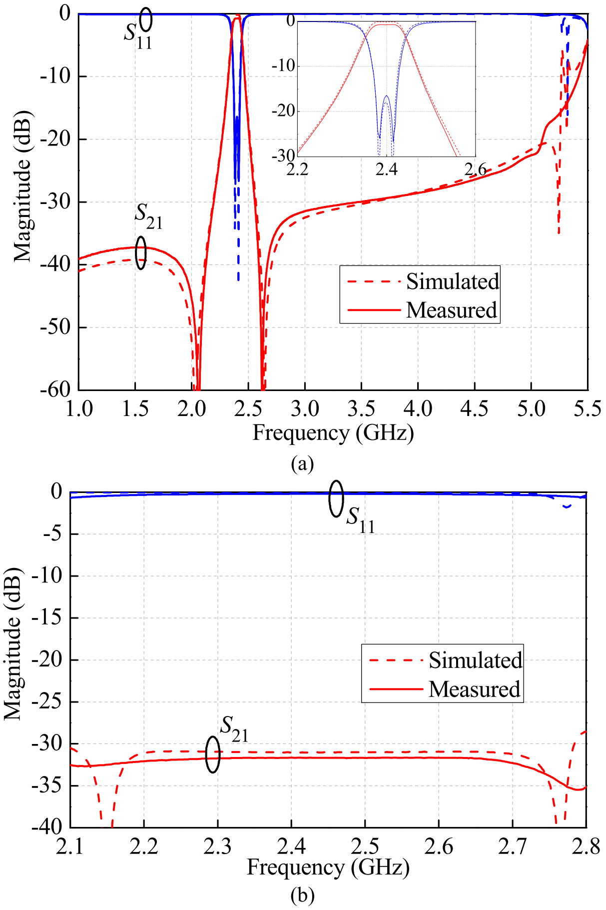


FIGURE 10. Experimental results of the filtering switch (a) ON-State; (b) OFF-State.

The measurement is accomplished by using the Keysight E5071C network analyzer. Fig. 10(a) shows the simulated and measured results in the ON-State where the PIN1 and PIN2 are reversed biased with the voltage of 12V. Good filtering responses are obtained. The measured passband is centered at 2.4 GHz. The measured minimum insertion loss is 0.67 dB, which is a bit higher than the simulated one (0.2 dB). It is due to the losses of SMA connectors and the losses in aluminum walls. The measured return loss is better than 16 dB and the corresponding 16-dB return loss FBW is 2%, showing good narrow-band bandpass responses and low loss. Two TZs are located in 2.06 and 2.62 GHz, which enhance the skirt selectivity. The stopband rejection is better than 20 dB from 2.51 to 5.1 GHz, featuring wide stopband.

TABLE 1. Comparison of various filtering switches.

Ref.	f_0 (GHz)	Filter orders	Insertion loss (dB)	FBW (%)	Stopband	Process	Size (λ_g^3)
[7]	0.901	4	1.8	14.3	3 f_0 (20 dB)	PCB	0.125 × 0.153 × N. A.
[12]	1.4	1	2.33	12	2.5 f_0 (22 dB)	LTCC	0.05 × 0.048×0.023
[15]	1.832	4	1	0.64	< 1.3 f_0	DR	0.79× 0.70 × N.A.
This work	2.4	2	0.67	2	2.1 f_0 (20 dB)	Coaxial resonator	0.368×0.216×0.24

N.A. means not available.

In the OFF-state, the measured results show good in-band isolation of better than 31 dB, as shown in Fig. 10(b). The switch time is less than 1μs.

Table 1 shows the comparison with some other filtering switches. Compared to the designs using PCB and LTCC technologies in [7] and [12], the proposed filtering switch realizes a narrower FBW with lower insertion loss (IL) due to the use of high Q factor coaxial resonators. Compared to the high-Q factor DR-based filtering switch in [15], this proposed design has smaller circuit size and it can achieve a wider stopband.

IV. CONCLUSION

This paper has presented a low-loss narrow-band filtering switch based on coaxial resonators. The detailed analysis of the filtering switch in the ON- and OFF-states has been presented. In the ON-state, good bandpass responses with two TZs located at both sides of the passband have been realized. In the OFF-state, high isolation has been achieved by loading the capacitors to the coaxial resonators. The circuit has been fabricated and measured. Measured results have shown that the proposed filtering switch features compact size, low loss, high selectivity and high isolation, which is attractive in wireless communication systems.

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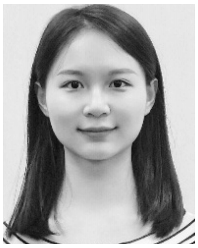

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