IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received September 8, 2017, accepted October 26, 2017, date of publication October 30, 2017, date of current version November 14, 2017.

Digital Object Identifier 10.1109/ACCESS.2017.2768098

Compact Filtering Switch With Wide-Stopband Response

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This work was supported in part by the National Natural Foundation of China under Grant 61671210, in part by the Science and Technology Planning Project of Guangdong Province under Grant 2017B090901053, and in part by the Science and Technology Program of Guangzhou under Grant 201604016112.

ABSTRACT A compact filtering switch with wide-stopband responses is presented in this paper. The resonator is designed using microstrip transmission lines and lumped capacitors. It is utilized to shift up the second harmonic frequency for wide-stopband performance and miniaturize the circuit size. In the ON-state, the circuit is the same as the bandpass filter without signals passing through the p-i-n diode, which avoids additional loss introduced by p-i-n diode. Two transmission zeros are generated near the passband to enhance the skirt selectivity. In the off-state, the signals from port 1 to port 2 passing through different transmission path are cancelled out, resulting in high isolation. For demonstration, a filtering switch operating at 780 MHz is implemented with the compact size of $0.072\lambda_g \times 0.066\lambda_g$. More than 20-dB suppression levels are measured from 0.89 to 5.3 GHz (6.8 f_0), featuring wide-stopband responses.

INDEX TERMS RF switch, bandpass responses, wide-stopband, lumped-element loaded resonator, compact size, high isolation.

I. INTRODUCTION

Switches and bandpass filters (BPFs) are essential components in many radio frequency (RF) front ends of wireless communication systems [1]–[5]. Generally, they are cascaded by the 50-Ω transmission line. To reduce the loss and size, the filtering switches, realized by the co-designs of switches and BPFs, have drawn much attention.

Recently, lots of researches have been conducted to design the filtering switches with compact size, low loss, high isolation or wide stopband responses. In [6], the switchable delay line is utilized for the high-isolation filtering switch. However, signals pass through the PIN diodes in the ON-state, which cost extra insertion loss. The ON- and OFF-states of the filtering switch are obtained by controlling the piezoelectric transducer in [7]. Compact size is realized. In [8] and [9], resonant frequencies of the resonators in high-order BPFs are controlled by PIN diodes to design filtering switches with wide stopband.

Since the above filtering switches [6]–[9] are designed using distributed microstrip transmission lines (TLs), it will be bulky in size if the operating frequencies is low. Due to the multilayer structure, low-temperature cofired ceramic (LTCC) techniques can be used to design the compact size filtering switch [10]. Besides, for miniaturization, the lumped elements can be used [11]. However, there are only a few filtering switches using lumped-element loaded resonators. In [12] and [13], the lumped capacitors are used as parts of the resonators and the OFF-state of the wide-stopband filtering switch can be realized by controlling the resonant frequencies of the resonators.

In this paper, we present a filtering switch using lumped-element loaded resonators. The lumped capacitors in the resonator not only reduce the circuit size but also move up the even-mode frequency of the resonator for wide stopband. Signals do not pass through the PIN diode in the ON-state, which avoids additional loss introduced by the PIN diode. Transmission zeros are generated near the passband, ensuring high selectivity. In the OFF state, signals from port 1 to port 2 are cancelled out to obtain high isolation. For verification, a filtering switch is implemented and the results are presented.

II. ANALYSIS OF THE FILTERING SWITCH

Fig. 1 shows the schematic of the presented filtering switch. There are two lumped-element loaded resonators which are comprised of the TLs and capacitors (C). Capacitors C_E are placed between resonators for the coupling

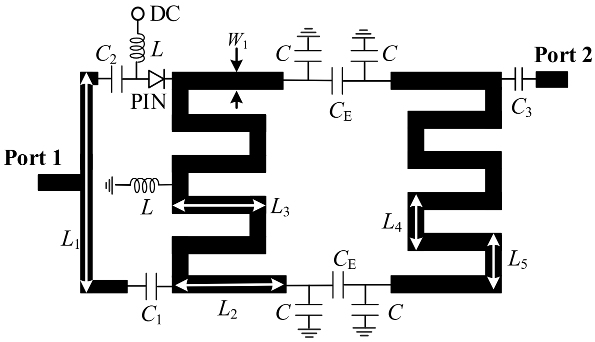

FIGURE 1. Schematic of the filtering switch.

coefficient control. C_1 and C_3 are connected to the resonators for controlling the input and output external quality factors. The ON- and OFF- states of the filtering switch are enabled by the switch circuitry including a capacitor (C_2), two inductors (L) and a PIN diode, as analyzed below.

A. ANALYSIS OF THE OFF-STATE RESPONSE

When the PIN diode is turned on, the filtering switch works in the OFF-state. For easy analysis, the parasitic effect of the PIN diode is ignored and thus the OFF-state equivalent circuit can be shown as Fig. 2 (a). It is seen that port 1 is connected to the resonator via two capacitors. To analyze the OFF-state responses, the circuit in Fig. 2 (a) can be separate as two symmetric and asymmetric structures, as shown in Figs. 2 (b) and (c), respectively.

The transmission characteristic of the lumped-element loaded resonator is firstly discussed. Fig. 2 (d) shows the voltage distribution and phase characteristic of the resonator at the fundamental resonance frequency. As seen, a voltage node exists at the center of the resonator and the voltage is out-of-phase with respect to the voltage node. When the signal pass through the voltage node, the phase shift is −180° [14]. Meanwhile, the electric coupling by C_E provides 90° phase shift. Accordingly, the phase shifts from port 1 to port 2 in Figs. 2 (b) and (c) are 90° and -90°, respectively [14]. When the locations of port 1 in Figs. 2 (b) and (c) are symmetric with respect to the voltage node and other design parameters are the same, the S_{21} in Figs. 2 (b) and (c) have the same amplitudes. For demonstration, simulated results of the symmetric and asymmetric structures in Figs. 2 (b) and (c) are shown in Figs. 3 (a) and (b), respectively. As seen, the phase of S_{21} are 90° and -90°, respectively, which agree well with the analysis. Accordingly, it can be concluded that in Fig. 2 (a), the signals from port 1 to port 2 through the two capacitor C' is out-of- phase and thus are cancelled out. The signals cannot be transferred from ports 1 to 2. The OFF-state isolation is realized.

For demonstration, the simulation of the OFF-state equivalent circuit in Fig. 2 (a) is carried out by ADS. Fig. 3 shows the simulated S_{21}. As seen, within the passband, the S_{21} is smaller than −35 dB, resulting in high OFF-state isolation. It is noted that the signal cancellation is realized by the two capacitors C' which connect port 1 and resonator 1. If higher-order bandpass responses are needed, other resonators can be design to couple with the resonator 2. In this way, the signal cancellation can still be remained to realize the OFF-state isolation. And thus the higher-order filtering switch can be realized by using this method.

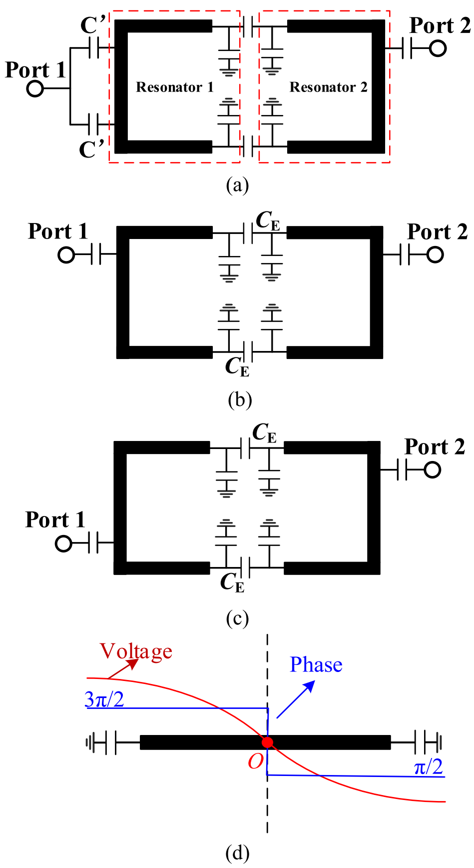

FIGURE 2. (a) OFF-state equivalent circuit; (b) Symmetric structure; (c) Asymmetric structure; (d) Voltage distribution and phase characteristic of the resonator.

B. ANALYSIS OF THE ON-STATE RESPONSE

When the PIN diode is turned off, the filtering switch works in the ON-state. Since signals cannot pass through the PIN diode, the switch circuitry is regarded as open-circuited. The filtering switch is equivalent to a BPF and the equivalent ON- state circuit can be illustrated as Fig. 4 (a). Conventional filter design method can be adopted. Fig. 4 (b) shows the structure of the lumped-element loaded resonator [11], which is symmetric. The even- and odd-mode analysis method can be applied to it and the odd- and even-mode equivalent circuits are shown as Figs. 2 (c) and (d), respectively. The odd- and even-mode input impedance can be expressed as

$$Y_{odd} = -jY_C \cot(\frac{\theta_1}{2} + \frac{\theta_2}{2}) + j\omega C \tag{1}$$

$$Y_{even} = jY_C \frac{\omega C + Y_C \tan(\frac{\theta_1}{2} + \frac{\theta_2}{2})}{Y_C - \omega C \tan(\frac{\theta_1}{2} + \frac{\theta_2}{2})} \tag{2}$$

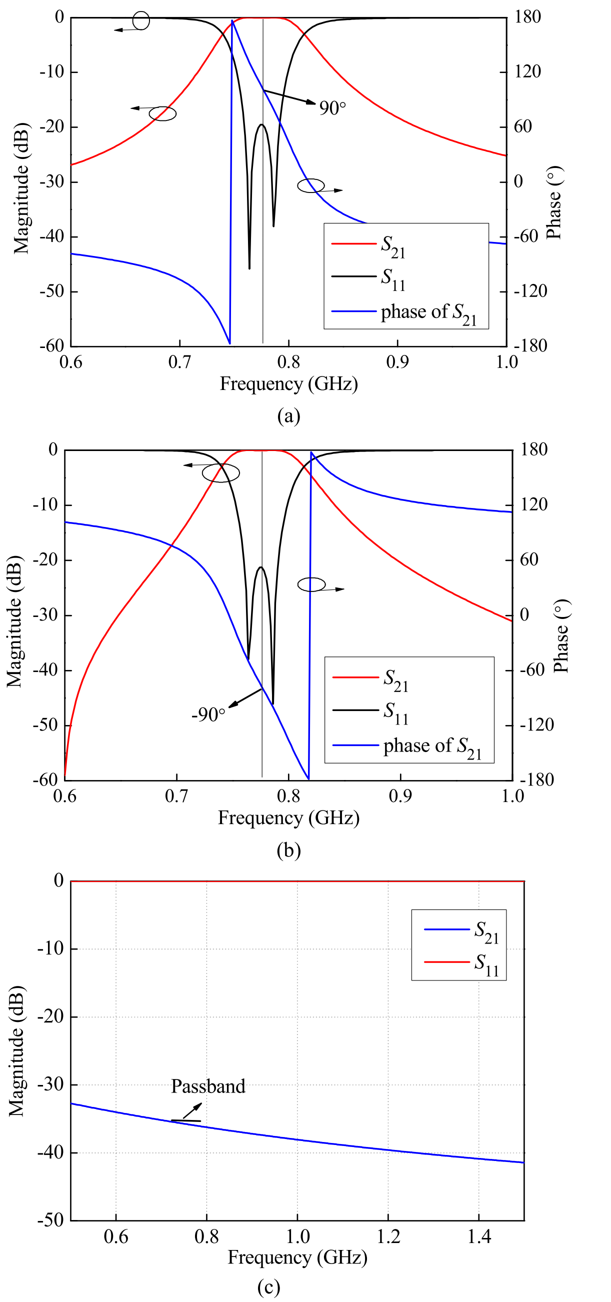

FIGURE 3. (a) Simulated results of the symmetric structure; (b) Simulated results of the asymmetry structure; (c) Simulated results of the OFF-state equivalent.

From the odd- and even-mode resonance conditions of $Y_{\rm odd} = 0$ and $Y_{\rm even} = 0$, the odd- and even-mode resonant frequencies ($f_{\rm odd}$ and $f_{\rm even}$) can be obtained by

$$2\pi f_{odd}(l_1 + l_2)\sqrt{\varepsilon_e}/c + 2\tan^{-1}(2\pi f_{odd} C/Y_C) = \pi \tag{3}$$

$$2\pi f_{even}(l_1 + l_2)\sqrt{\varepsilon_e}/c + 2\tan^{-1}(2\pi f_{even} C/Y_C) = 2\pi \tag{4}$$

where c is the speed of light in free space, $Y_{\rm C}$ denotes the characteristic admittance of the transmission lines and $\varepsilon_{\rm e}$ is the effective dielectric constant. From (3), it can be noted that the length of $(l_1 + l_2)$ can be reduced by increasing the value

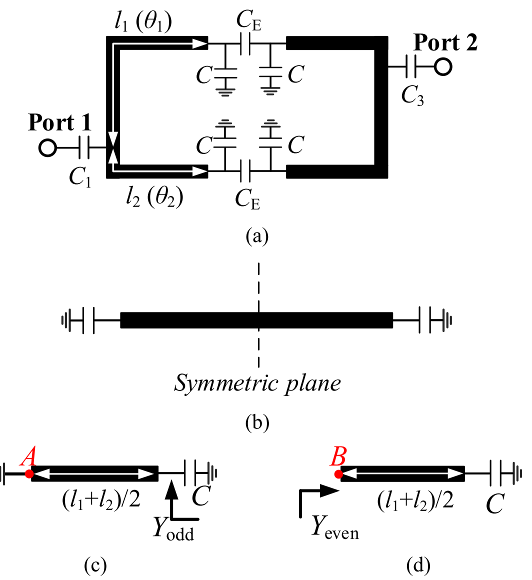

FIGURE 4. (a) Equivalent circuit in the ON-state; (b) Structure of the quasi-lumped resonator; (c) Odd-mode equivalent; (d) Even-mode equivalent.

of the capacitor C. Meanwhile, according to (4), when C is increased, $f_{\rm even}$ can be extended to the higher frequency. Thus, by properly selecting the length of $(l_1 + l_2)$ and the value of C, the quasi-lumped resonator can not only miniaturize the circuit size but also realize wide stopband performance.

After designing the resonator, the coupling coefficient (k) and the external quality factor ($Q_{\rm e}$) are controlled to realize good bandpass responses. Based on the desired responses, the lumped values of the second-order prototype filter are selected to be: $g_0 = 1$, $g_1 = 0.843$, $g_2 = 0.622$, $g_3 = 1.3554$. According to the operating frequency $f_0 = 780$ MHz and fractional bandwidth FBW $= 9.5\%$, k and $Q_{\rm e}$ can be calculated as [15]

$$Q_e = \frac{g_0 g_1}{FBW} = 8.8 \tag{5}$$

$$k = \frac{FBW}{\sqrt{g_1 g_2}} = 0.72 \tag{6}$$

Based on the calculated values of k and $Q_{\rm e}$, general layout of the filtering switch can be determined. In this design, two capacitors ($C_{\rm E}$) are placed between the two quasi-lumped resonators, which provide electric coupling. Thus, the coupling coefficient k can be easily controlled by the value of $C_{\rm E}$. As for the $Q_{\rm e}$, it is determined by the tap position of the input and output ports, namely, the length of l_1 and l_2, as well as the values of C_1 and C_3. Accordingly, the desired bandpass responses are obtained. Moreover, it is noted that the input and output ports are asymmetric. Two transmission zeros can be generated near the passband [11], which enhance the skirt selectivity.

To verify the above analysis, simulation of the equivalent circuit in the ON-state in Fig. 4 (a) is carried out. The initial parameters are selected as follows: $\theta_1 = 26.35°$, $\theta_2 = 5.27°$,

$C = 13.5$ pF, $C_E = 1$ pF, $C_1 = C_3 = 50$ pF. $Y_C = 0.02$ S, where θ_1 and θ_2 are calculated corresponding to the operating frequency 780 MHz. Fig. 5 shows the simulated results of the ON-state equivalent circuit. As seen, the passband is centered at 780 MHz with the 3-dB fractional bandwidth of 9.5%. Two transmission zeros are generated near the passband, which enhance the skirt selectivity. Due to the using of lumped capacitors C, the second harmonic is at 4.6 GHz, resulting in wide stopband responses.

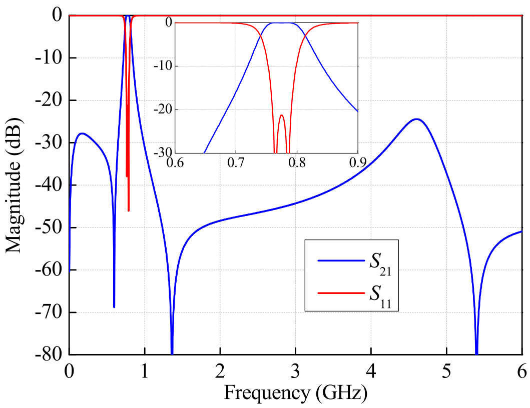

FIGURE 5. Simulated results of the ON-state equivalent circuit.

III. IMPLEMENTATION

Based on the above analysis, a compact wide-stopband filtering switch using lumped-element loaded resonators is designed following the design procedures below. Firstly, with a given fundamental frequency (f_{odd}) and the second harmonic (f_{even}), C and ($l_1 + l_2$) are determined based on (3) and (4) and a selected Y_C. Secondly, the locations of ports 1 and 2 as well as values of C_1 and C_3 are selected to realize the desired ON-state Q_e. The value of C_E is tuned to meet the requirement k. Then, the switch circuitry including C_2, L and PIN diode is added to enable the control of ON- and OFF-states. Finally, fine tuning is performed to obtain good ON- and OFF-state performance.

In the experiment, the substrate of Rogers 4003 is used with a relative dielectric constant of 3.38, loss tangent of 0.0027 and thickness of 0.81 mm. The dimensions (all in mm) and the lumped elements are selected as follows: $L_1 = 11, L_2 = 6, L_3 = 3.7, L_4 = 3, L_5 = 3, W_1 = 1, C = 7.5$ pF, $C_E = 0.8$ pF, $C_1 = C_2 = C_3 = 10$ pF, $L = 270$ nH. The PIN diode used in this design is SMP1345-079LF from Skyworks. The Murata LC lumped components are used in the implementation with the package size of 0402. The photograph of the fabricated circuit is shown in Fig. 6. The circuit has compact size is 17×15.5 mm^2 (or $0.072\ \lambda_g \times 0.066\ \lambda_g$).

The simulation and measurement are accomplished by ADS and Agilent E5071C network analyzer, respectively. Fig. 7 shows the simulated and measured results. In the ON-state, the measured passband is centered at 0.78 GHz with the 3-dB fractional bandwidth of 9 %. The insertion loss is 1.8 dB and the return loss is better than 10 dB. It should be noted that the insertion loss in the proposed design only

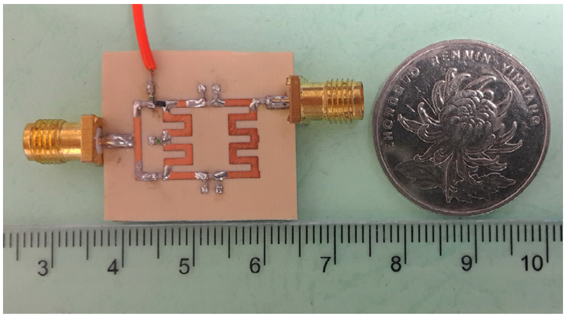

FIGURE 6. Photograph of the fabricated filtering switch.

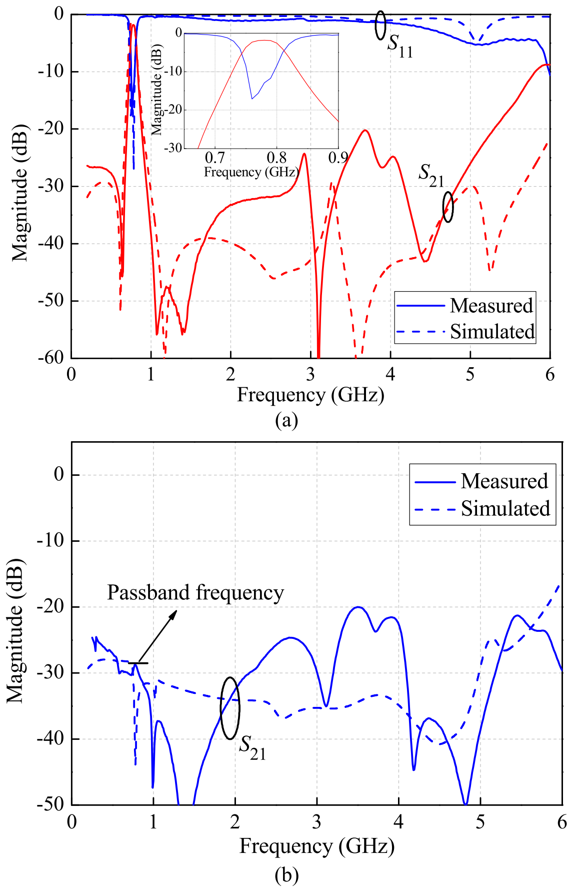

FIGURE 7. Simulated and measured results (a) ON-state; (b) OFF-state.

includes the filter loss, because the PIN diode is turned off in the ON-state and the signals do not pass through the PIN diode. As compared to the conventional cascaded filter and switch, the switch loss is eliminated. Two transmission zeros are generated at two sides of the passband, which enhance the skirt selectivity. More than 20 dB rejection are realized from 0.83 GHz to 5.3 GHz (6.8 f_0), resulting in wide stopband. In the OFF-state, the isolation is better than 28 dB within the passband and more than 20 dB from 0.3 GHz to 6 GHz. It is noted that the measured S_{21} is slightly different from the simulated one. It may be due to the fabrication tolerance and inaccuracy of the lumped element models in ADS simulation. As for the switch time, it is less than 1 μs.

TABLE 1. Comparison with some other filtering switches.

Ref.	Filter orders	PIN-diode numbers	Additional loss (ON)	Stopband	Electrical size (λ_g^2)
[6]	2	2	Yes	$< 2\,f_0$	0.27 × 0.25
[7]	2	-	No	$< 2\,f_0$	0.33 × 0.33
[8]	4	1	Yes	$7.7\,f_0$ (30 dB)	1 × ~
[9]	4	2	No	$7\,f_0$ (30 dB)	0.4 × 0.27
	4	2	No	$9\,f_0$ (30 dB)	0.39 × 0.32
[12] (SPDT)	3	4	No	$4\,f_0$ (25 dB)	0.54 × 0.50
This work	2	1	No	$6.8\,f_0$ (20 dB)	0.072 × 0.066

Additional loss means that the signals pass through the PIN diodes in the ON-state and cause extra loss.

Table I tabulates the comparison with some other works. In [6] and [7], since the harmonic is not manipulated, the stopband is narrow. In [8] and [9], better than 30 dB out-of-band rejection are realized wider than 7 f_0 whereas the OFF-state is realized by changing the resonant frequencies of the resonators and thus high-order BPFs are needed, resulting in larger circuit size. In [12], a SPDT filtering switch is also realized using the capacitor-loaded resonators, which features compact size (excludes the bias circuits). However, three order filter is required to realize high OFF-state isolation. Compared to [6] and [8], signals do not pass through the PIN diode in the proposed design in the ON-state, the additional loss by the PIN diode is eliminated. By using the lumped-element loaded resonators, the circuit size in our design is much smaller than that in [6]–[9]. In sum, the proposed design features compact size, wide stopband and simple structure, which is suitable for the wireless communication systems.

IV. CONCLUSION

This letter has presented a method for designing the filtering switch using lumped-element loaded resonators. The detailed analysis of the ON- and OFF-state responses as well as the design procedures have been given. The PIN diode does not introduce extra loss in the ON-state and the signals from port 1 to port 2 are cancelled out in the OFF-state to obtain high- isolation. The circuit implementation has indicated that the proposed filtering switch exhibits compact size, simple structure and wide-stopband performance.

REFERENCES

[1] S. W. Wong *et al.*, "Individually frequency tunable dual- and triple-band filters in a single cavity," *IEEE Access*, vol. 5, pp. 11615–11625, 2017.

[2] Z.-C. Guo *et al.*, "Triple-mode cavity bandpass filter on doublet with controllable transmission zeros," *IEEE Access*, vol. 5, pp. 6969–6977, 2017.

[3] B. J. Xiang, W. J. Liu, S. Y. Zheng, Y. M. Pan, Y. X. Li, and Y. L. Long, "Vias and stubs loaded patch and its applications in filter and rectifier designs," *IEEE Access*, vol. 5, pp. 7042–7054, 2017.

[4] Y. Wu, L. Cui, W. Zhang, L. Jiao, Z. Zhuang, and Y. Liu, "High performance single-ended wideband and balanced bandpass filters loaded with stepped-impedance stubs," *IEEE Access*, vol. 5, pp. 5972–5981, 2017.

[5] B. Yu *et al.*, "DC-30 GHz DPDT switch matrix design in high resistivity trap-rich SOI," *IEEE Trans. Electron Devices*, vol. 64, no. 9, pp. 3548–3554, Sep. 2017.

[6] W.-H. Tu, "Switchable microstrip bandpass filters with reconfigurable on-state frequency responses," *IEEE Microw. Wireless Compon. Lett.*, vol. 20, no. 5, pp. 259–261, May 2010.

[7] W. H. Tu and K. Chang, "Piezoelectric transducer-controlled dual-mode switchable bandpass filter," *IEEE Microw. Wireless Compon. Lett.*, vol. 17, no. 3, pp. 199–201, Mar. 2007.

[8] Y.-S. Lin, P.-Y. Chang, and Y.-S. Hsieh, "Compact electronically switchable parallel-coupled microstrip bandpass filter with wide stopband," *IEEE Microw. Wireless Compon. Lett.*, vol. 18, no. 4, pp. 254–256, Apr. 2008.

[9] S.-F. Chao, C.-H. Wu, Z.-M. Tsai, H. Wang, and C. H. Chen, "Electronically switchable bandpass filters using loaded stepped-impedance resonators," *IEEE Trans. Microw. Theory Techn.*, vol. 54, no. 12, pp. 4193–4201, Dec. 2006.

[10] J.-X. Xu and X. Y. Zhang, "Single- and dual-band LTCC filtering switch with high isolation based on coupling control," *IEEE Trans. Ind. Electron.*, vol. 64, no. 4, pp. 3137–3146, Apr. 2017.

[11] K.-X. Wang, X. Y. Zhang, S. Y. Zheng, and Q. Xue, "Compact filtering rat-race hybrid with wide stopband," *IEEE Trans. Microw. Theory Techn.*, vol. 63, no. 8, pp. 2550–2560, Aug. 2015.

[12] C.-S. Chen, J.-F. Wu, and Y.-S. Lin, "Compact single-pole-double-throw switchable bandpass filter based on multicoupled line," *IEEE Microw. Wireless Compon. Lett.*, vol. 24, no. 2, pp. 87–89, Feb. 2014.

[13] J.-F. Wu and Y.-S. Lin, "On-chip bandpass single-pole-double-throw switch based on multicoupled line," in *IEEE MTT-S Int. Microw. Symp. Dig.*, San Francisco, CA, USA, May 2016, pp. 1–4.

[14] Y. C. Li, Q. Xue, and X. Y. Zhang, "Single- and dual-band power dividers integrated with bandpass filters," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 1, pp. 69–76, Jan. 2013.

[15] J. S. Hong and M. J. Lancaster, *Microwave Filters for RF/Microwave Applications*. New York, NY, USA: Wiley, 2011.

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