High Selectivity Dual-band Bandpass Filters Using Dual-mode Resonators

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***Abstract* –** Two high selectivity dual-band bandpass filters using dual-mode resonators are proposed in this paper. Four and six transmission zeros near the passbands can be easily achieved for two dual-band bandpass filters. A transmission zero located in the two passbands is used to realize good isolation for the two passbands. Two prototypes with center frequencies located at 1.93, 2.42 GHz, and 2.04, 2.32 GHz with upper stopband insertion loss greater than 20 dB are designed and fabricated. The two proposed dual-band bandpass filters show high passband selectivity, good out-of-band suppression.

***Index Terms* –** Bandpass filter, dual-band, dual-mode, transmission zeros.

I. INTRODUCTION

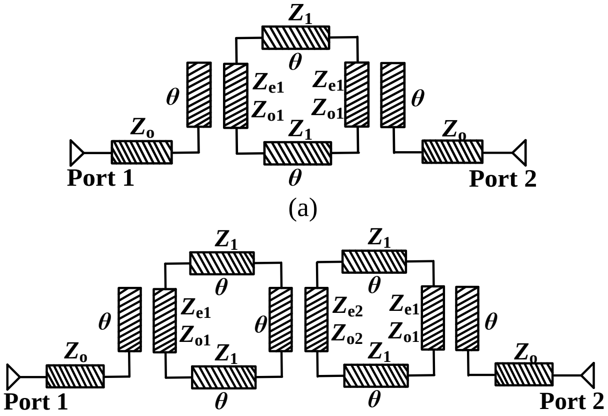
Dual-band bandpass filters are becoming more and more important with the rapid development microwave communication systems [1]-[6]. The main attentions for dual-band bandpass filter design are the passband selectivity, passband isolation, upper stopband, and bandwidth control. Dual-mode ring resonators have a lot of attractive features such as compact circuit size, transmission zeros near passbands, which are firstly proposed by Wolff [7]. The dual-mode ring resonators have been introduced to design different bandpass filters, balanced circuits, power dividers [8]-[12] in the past few years. As discussed in [9], coupled ring resonators can be easily used to design high performance dual-band bandpass filters, several resonators can be configured in series, in parallel or both to realize different transmission characteristic. However, the dual-band bandpass filters have only two transmission zeros near each passband, cascaded ring resonators can only increase the passband-order, the out-of-band transmission zeros are difficult to increase.

In this paper, two novel dual-band bandpass filters with multiple transmission zeros are proposed, two dual-mode ring resonators are used to realize the two passbands, and loaded shorted stubs and coupled lines are used to increase the numbers of transmission zeros. Pairs of independently adjusted transmission zeros can be easily realized for the two dual-band filters. Two prototypes of the dual-band bandpass filters are constructed on the dielectric substrate with $\varepsilon_r = 2.65$, $h = 1.0$ mm, and $\tan\delta = 0.003$.

II. ANALYSIS OF PROPOSED DUAL-BAND FILTERS

A. Bandpass filters using dual-mode resonators

Figures 1 (a)-(b) shows the ideal circuits of the bandpass filters using dual-mode ring resonators, and the dual-mode ring resonators are attached to two quarter-wavelength side-coupled lines (electrical length θ, even/odd-mode characteristic impedance Z_{e1}, Z_{o1}). Two transmission lines (Z_1, θ) are located in the middle of the filter circuits, two microstrip lines with characteristic impedance $Z_0 = 50\ \Omega$ are connected to ports 1, 2.



(a)

(b)

Fig. 1. (a) Bandpass filter circuit using single dual-mode ring resonator [8], and (b) dual-band filter using series dual-mode ring resonators [9].

The simulated results of Figs. 1 (a)-(b) are shown in Fig. 2, the two transmission zeros near the passband can be calculated as:

$$\theta_{tz1} = \arccos\sqrt{\frac{Z_{e1}+Z_{o1}-2Z_1}{Z_{e1}+Z_{o1}+2Z_1}}\ ,\ \theta_{tz2} = \pi - \theta_{tz1}\,. \qquad (1)$$

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And when two dual-mode ring resonators are in series, a transmission zero (f_0) can be realized in the center frequency of the bandpass filter, and two passbands can be easily realized [9]. In addition, due to the cascaded dual-mode ring resonators, the out-of-band performance rejection has been further improved. However, due to the circuit limitation, the out-of-band performance cannot be further improved for lack of transmission zeros out-of-band. Next, two improved dual-band filters with four and six transmission zeros will be given.

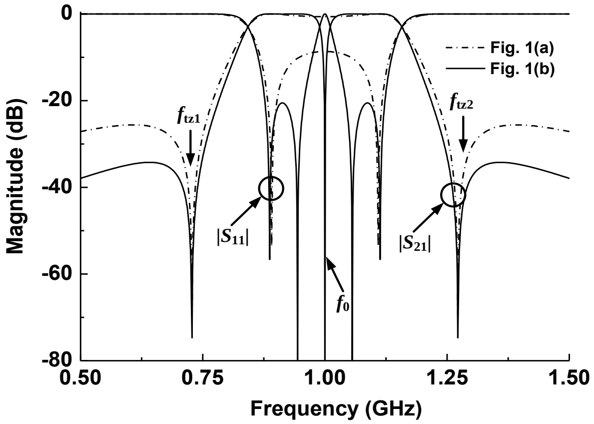
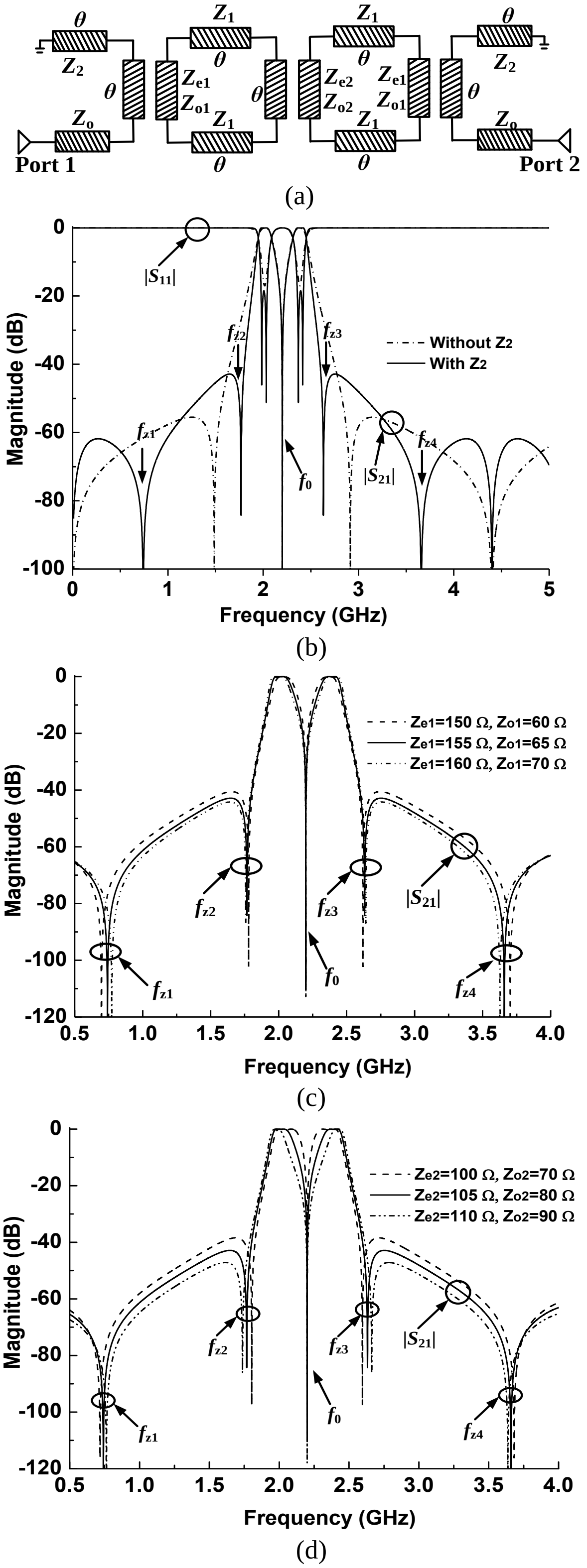


Fig. 2. Simulated results of the bandpass filters of Fig. 1, (Z_1 = 90/90 Ω, Z_{e1} = 182 Ω, Z_{o1} = 72 Ω, Z_{e2} = 182 Ω, Z_{o2} = 72 Ω, Z_0 = 50 Ω).

B. Proposed two dual-band bandpass filters

The ideal circuit of the dual-band bandpass filter with four transmission zeros are shown in Fig. 3 (a), and two shorted stubs (Z_2, θ) are located in the end of the side-coupled lines. The other parts are the same as Fig. 1 (b). The simulated frequency responses of the dual-band bandpass filter with five transmission zeros are shown in Figs. 3 (b)-(e), and besides the transmission zeros located at f_0, four transmission zeros (f_{z1}, f_{z2}, f_{z3}, f_{z4}, $f_{z1}+f_{z4}=2f_0$, $f_{z2}+f_{z3}=2f_0$) are realized due to the loaded shorted stubs Z_2. Due to the complex transmission matrix of the cascaded two dual-mode ring resonators, the equations of transmission zeros of the center frequencies of Fig. 3 (a) are difficult to solve out directly. From the simulated results of Figs. 3 (b)-(e), we can find that, the center frequency of the two passbands move towards f_0 as Z_1 increases, and the bandwidth of the two passband increases as the sum of Z_{e2}, and Z_{o2} increases. Moreover, the two transmission zeros f_{z1}, f_{z4} move away from f_0 as sum of Z_{e1}, and Z_{o1} decreases, and the two transmission zeros f_{z2}, f_{z3} move away from f_0 as the sum of Z_{e2}, and Z_{o2} increases. The passband selectivity and out-of-band harmonic suppression have been improved due to the increased transmission zeros.

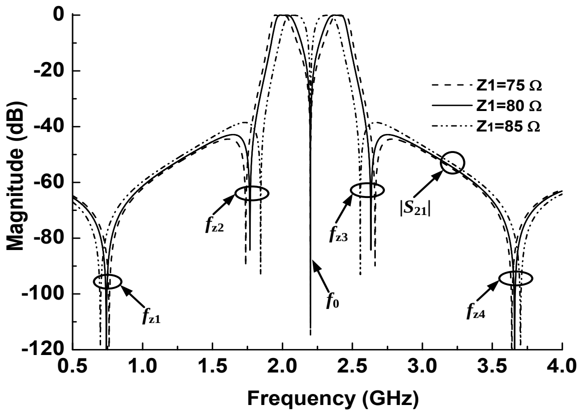


(a)

(b)

(c)

(d)



(e)

Fig. 3. (a) Ideal circuit of the dual-band filter with five transmission zeros, (b) simulated results of Fig. 1 (b) and Fig. 3 (a), (c) $|S_{21}|$ versus Z_{e1}, Z_{o1}, (d) $|S_{21}|$ versus Z_{e2}, Z_{o2}, and (e) $|S_{21}|$ versus Z_1, ($Z_1 = 80\ \Omega$, $Z_2 = 120\ \Omega$, $Z_{e1} = 155\ \Omega$, $Z_{o1} = 65\ \Omega$, $Z_{e2} = 105\ \Omega$, $Z_{o2} = 80\ \Omega$, $Z_0 = 50\ \Omega$).

The proposed dual-band bandpass filter with seven transmission zeros is illustrated in Fig. 4 (a), and two open/shorted coupled lines (electrical length θ, even/odd-mode characteristic impedance Z_{e3}, Z_{o3}), and the input impedance of the open/shorted coupled lines is:

$$Z_{in} = j\frac{(Z_{e3}+Z_{o3})^2\cos^2\theta-(Z_{e3}-Z_{o3})^2}{(Z_{e3}+Z_{o3})\sin 2\theta}. \qquad (2)$$

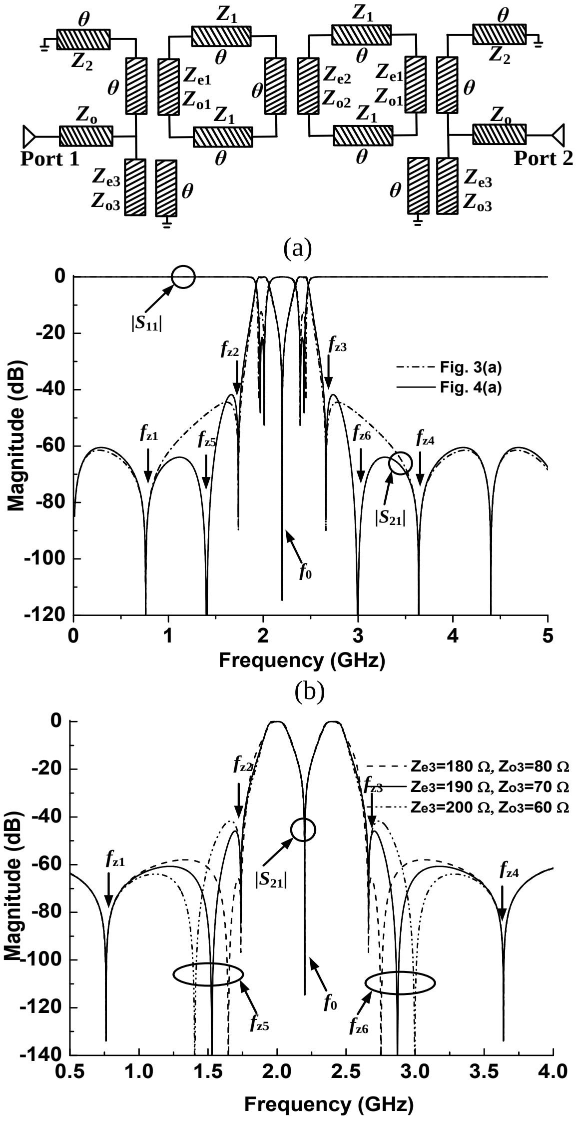
When $Z_{in} = 0$, two transmission zeros can be obtained as:

$$\theta_{z5} = \arccos\sqrt{\frac{Z_{e3}-Z_{o3}}{Z_{e3}+Z_{o3}}},\ \theta_{z6} = \pi-\theta_{z5}, \qquad (3)$$

and the two transmission zeros (f_{z5}, f_{z6}) have only relationship with Z_{e3}, Z_{o3}, which are two independently adjusted transmission zeros for the dual-band bandpass filter with seven transmission zeros.

The simulated frequency responses of the two dual-band bandpass filters are shown in Figs. 4 (b)-(c), and the two transmission zeros f_{z5}, f_{z6} are located in the center of f_{z1}, f_{z2}, f_{z3}, f_{z4}, the out-of-band harmonic suppression can be easily improved, and the bandwidth of the two passbands and center frequencies do not change with f_{z5}, f_{z6} [8], which can supply more freedom for the bandpass filter design.

Based on the above discussions and analysis, the center frequencies of the two dual-band filters are chosen as: 1.94 and 2.42 GHz, 2.04 and 2.34 GHz, and the prototypes of the proposed two dual-band bandpass filters are shown in Figs. 5 (a)-(b), and the final parameter for the two dual-band bandpass filters are shown in Table 1. The simulated results of the two dual-band bandpass filters are shown in Figs. 6 (a)-(b), for the dual-band bandpass filter with five transmission zeros, the center frequencies are located at 1.93 GHz and 2.42 GHz, the 3-dB bandwidths of the two passbands are 8.3% (1.86-2.02 GHz) and 5.0% (2.35-2.47 GHz), and five transmission zeros are located at 0.70 GHz, 1.64 GHz, 2.21 GHz, 2.60 GHz, and 3.53 GHz, and the upper stopband insertion loss is greater than 35 dB from 2.57 GHz to 6.0 GHz. For the dual-band bandpass filter with seven transmission zeros, the 3-dB bandwidths of the two passbands are 8.1% (1.965-2.13 GHz), 5.1% (2.26-2.38 GHz), seven transmission zeros are located at 0.55 GHz, 1.49 GHz, 1.68 GHz, 2.21 GHz, 2.51 GHz, 3.58 GHz, and 4.18 GHz, and the upper stopband insertion loss is greater than 30 dB from 2.48 to 6.1 GHz, compared with the dual-band filter with five transmission zeros, the passband selectivity have been further improved.

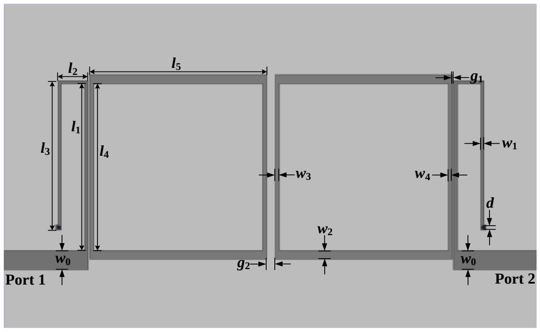


(a)

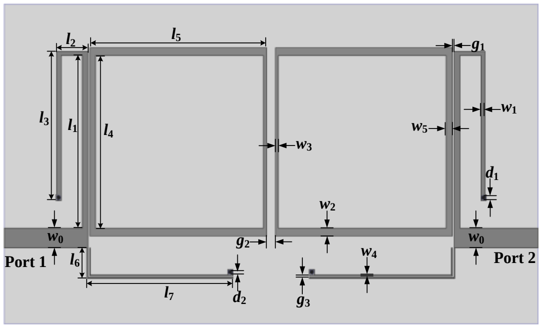
(b)

(c)

Fig. 4. (a) Ideal circuit of the dual-band filter with seven transmission zeros, (b) simulated results of Fig. 3 (a) and Fig. 4 (a), (c) $|S_{21}|$ versus Z_{e3}, Z_{o3}, ($Z_1 = 80\ \Omega$, $Z_2 = 120\ \Omega$, $Z_{e1} = 155\ \Omega$, $Z_{o1} = 65\ \Omega$, $Z_{e2} = 105\ \Omega$, $Z_{o2} = 80\ \Omega$, $Z_{e3} = 200\ \Omega$, $Z_{o3} = 60\ \Omega$, $Z_0 = 50\ \Omega$).

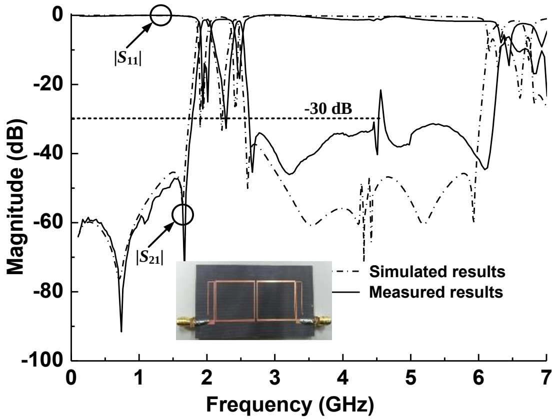


(a)

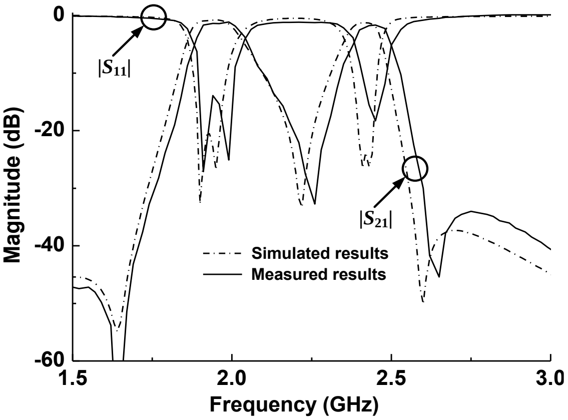


(b)

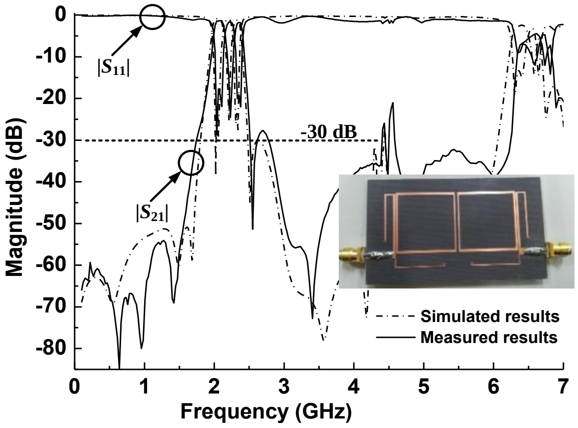
Fig. 5. Geometries of the two dual-band bandpass filters, (a) five zeros and (b) seven zeros.



(a)-I



(a)-II



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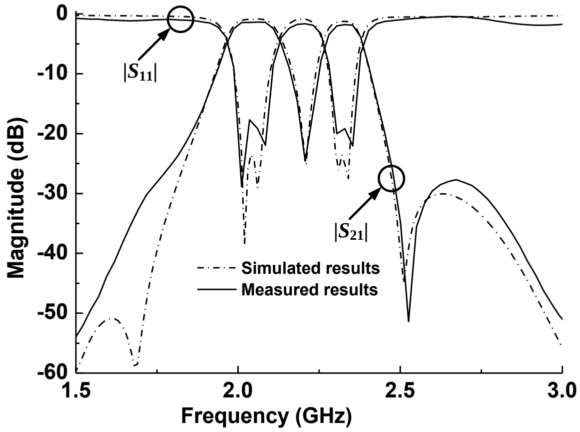

(b)-II

Fig. 6. Photographs, simulated and measured results of the two dual-band bandpass filters, (a) five zeros and (b) seven zeros.

Table 1: Parameters of the proposed two filters ($\varepsilon_r = 2.65$, $h = 1.0$ mm, and tan $\delta = 0.003$)

Proposed Filters	Circuit Parameters (Ω)	Structure Parameters (mm)
Five zeros	$Z_0 = 50$, $Z_1 = 80$, $Z_2 = 125$, $Z_{e1} = 151$, $Z_{o1} = 60$, $Z_{e2} = 125$, $Z_{o2} = 95$	$l_1 = 23.6$, $l_2 = 4.2$, $l_3 = 20.4$, $l_4 = 23.6$, $l_5 = 24.7$, $w_0 = 2.7$, $w_1 = 0.42$, $w_2 = 1.24$, $w_3 = 0.56$, $w_4 = 0.56$, $g_1 = 0.19$, $g_2 = 1.2$, $d = 0.6$
Seven zeros	$Z_0 = 50$, $Z_1 = 85$ $Z_2 = 11$, $Z_{e1} = 135$, $Z_{o1} = 55$, $Z_{e2} = 135$, $Z_{o2} = 100$, $Z_{e3} = 230$, $Z_{o3} = 88$	$l_1 = 23.6$, $l_2 = 4.4$, $l_3 = 20.0$, $l_4 = 23.6$, $l_5 = 24.9$, $l_6 = 4.2$, $l_7 = 20.5$, $w_0 = 2.7$, $w_1 = 0.6$, $w_2 = 1.06$, $w_3 = 0.46$, $w_4 = 0.15$, $w_5 = 0.84$, $g_1 = 0.24$, $g_2 = 1.2$, $g_3 = 0.2$, $d_1 = 0.6$, $d_2 = 0.6$

III. EXPERIMENT AND RESULTS DISCUSSIONS

The photographs, measured results of the two dual-band bandpass filters are also illustrated in Fig. 6. Good agreements can be observed between the simulation and the experiments. For the dual-band bandpass filters with five transmission zeros, five transmission zeros are located at 0.74 GHz, 1.67 GHz, 2.28 GHz, 2.67 GHz, and 3.21 GHz, the 3-dB bandwidths of the two passbands are 8.1% (1.90-2.06 GHz) and 5.3% (2.40-2.53 GHz), and the upper stopband insertion loss greater than 20 dB from 2.6 GHz to 6.26 GHz; for the dual-band bandpass filter with seven transmission zeros, the 3-dB bandwidths of the two passbands are 8.2% (1.99-2.16 GHz) and 5.1% (2.29-2.41 GHz), seven transmission zeros are located at 0.64 GHz, 0.96 GHz, 1.42 GHz, 2.23 GHz, 2.55 GHz, 3.15 GHz, and 3.41 GHz, the upper stopband insertion loss is greater than 20 dB from 2.46 GHz to 6.28 GHz.

Moreover, Table 2 illustrates the comparisons of measured results for several dual-band bandpass filter structures. Compared with other balanced filters [1], [2], [3], [6], [9], the proposed two dual-band bandpass filters have more transmission zeros near the passbands, and the upper stopband for the two bandpass filters can stretch up to $3.3f_1$ ($|S_{21}| < -20$ dB) and $3.1f_1$ ($|S_{21}| < -20$ dB), respectively. Further circuit size reduction can be also realized by using folded lines in multi-layer circuits.

Table 2: Comparisons of measured results for some dual-band filters

Filter Structures	TZs, $\|S_{21}\|$	Bandwidth (%)	Stopband $\|S_{21}\|$, dB	Center Frequencies (GHz)
Ref. [1]	5	14%,10%	<-20, $3.0f_1$	1.80, 3.50
Ref. [2]	2	2.0%, 3.0%	<-20, $1.6f_1$	0.87, 1.27
Ref. [3]	3	25.7%, 15.3%	< -20, $3.0f_1$	1.32, 2.67
Ref. [6]-I	4	8.55%, 5.93%	<-20, $2.7f_1$	1.87, 2.53
Ref. [9]	3	5.3%, --	<-20, $3.0f_1$	2.0, 4.0
These works	5	8.1%, 5.3%	<-20, $3.3\ f_1$	1.93, 2.42
	7	8.2%, 5.1%	<-20, $3.1\ f_0$	2.04, 2.32

IV. CONCLUSION

In this paper, two novel high selectivity dual-band bandpass filters with multiple transmission zeros using dual-mode resonators are proposed. Five and seven transmission zeros from direct current to second harmonic can be used to realize high passband selectivity, and the bandwidth and center frequencies of the two passbands can be adjusted independently by changing the coupling even/odd mode of the coupled lines and characteristic impedance of the ring resonators. The proposed dual-band bandpass filters have advantages of high selectivity, wide upper stopband, simple structure, and high passband isolation. Good agreements between simulated and measured responses of the structures are demonstrated, indicating good candidates for planar microwave dual-band circuits and systems.

ACKONWLEGEMENT

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