Bandpass Filter Loaded With Open Stubs Using Dual-mode Ring Resonator

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***Abstract*—A high selectivity bandpass filter loaded with open stubs using dual-mode ring resonator is presented in this letter. Sixth-order passband with six transmission zeros close to the passband is realized with two open stubs and open/shorted coupled lines. The transmission zeros near the passband can be adjusted conveniently by only changing the characteristic impedances of the coupled lines. For demonstration, a planar bandpass filter (3 dB bandwidth 20.6%) is designed and fabricated. Good filtering performance and high selectivity for the filter are realized and experimentally verified.**

***Index Terms*—Coupled lines, dual-mode, ring resonator, stubs, transmission zeros.**

I. Introduction

Dual-mode bandpass filter is one of typical microwave filters with two inherent transmission zeros close to the passband [1], which has many attractive advantages such as low radiation loss, high Q factor, compact size and sharp rejection shirts. The dual-mode resonator was firstly introduced in [1], [2], in which two degenerated modes can be excited by introducing a perturbation element along an orthogonal plane of resonator; different ring resonators with open stubs and notches were used to design wideband bandpass filters with high selectivity [3]–[6]. In addition, ring resonators loaded based on transversal signal-interaction concepts can realize more pairs of out-of-band transmission zeros [7]–[10], due to the passband constructive interference and out-of-band signal energy cancellations. Moreover, dual-mode resonator using side-coupled lines was used to design bandpass filters without any perturbations [11], [12], however, numbers of ring resonators must be used to increase the passband-order, which increase the circuit size, and out-of-band transmission zeros cannot increase simultaneously.

In this letter, a novel bandpass filter loaded with open stubs using dual-mode ring resonator is proposed. A sixth-order passband can be easily realized with only a ring resonator, while two half-wavelength open stubs, and open/shorted coupled lines are used to realize four additional transmission zeros close to the passband. The four out-of-band transmission zeros can be adjusted conveniently by changing the even/odd-mode coupled line impedances. A prototype of the bandpass filter operating at 3.2 GHz is constructed on the dielectric substrate with $\varepsilon_r = 2.65$, $h = 1.0$ mm, and $\tan\delta = 0.003$.

Manuscript received January 06, 2015; revised February 16, 2015, February 25, 2015; accepted February 28, 2015. Date of publication April 07, 2015; date of current version May 06, 2015. This work was supported by the 2012 Distinguished Young Scientist awarded by the National Natural Science Foundation Committee of China(61225001), and by the National Natural Science Foundation of China (6140010914), Natural Science Foundation of Jiangsu Province (BK20140791) and the 2014 Zijin Intelligent Program of Nanjing University of Science and Technology.

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Digital Object Identifier 10.1109/LMWC.2015.2410174

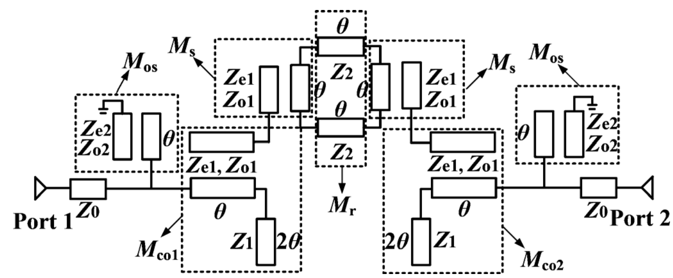


Fig. 1. The ideal circuit of the bandpass filter.

II. Proposed Bandpass Filter Loaded With Open Stubs

The bandpass filter loaded with open stubs is shown in Fig. 1. A dual-mode ring resonator is attached to two quarter-wavelength side-coupled lines (electrical length θ, even/odd-mode characteristic impedance $Z_{\rm e1}, Z_{\rm o1}$). Two half-wavelength open stubs are connected in the end of the side-coupled lines, and two open/shorted coupled lines (electrical length θ, even/odd-mode characteristic impedance $Z_{\rm e2}, Z_{\rm o2}$) are shunted connected in the input/output Ports 1, 2. The characteristic impedances of the two microstrip lines at the input/output ports are all $Z_0 = 50\,\Omega$.

A. In-Band and Out-of-Band Performance Analysis

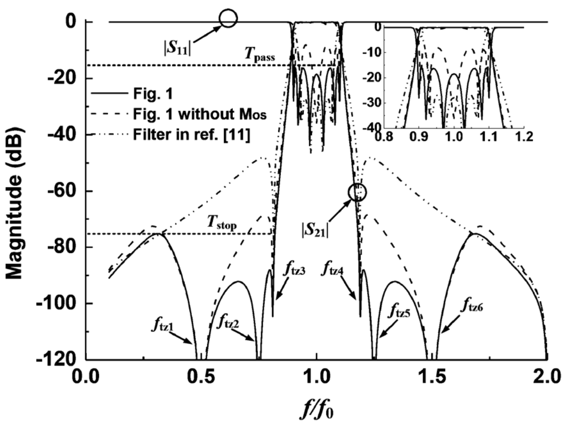
The center ring resonator of the bandpass filter is similar as the bandpass filter in [11]. The *ABCD* matrix of the bandpass filter circuit for Fig. 1 can be defined as $M_{\rm os} \times M_{\rm co1} \times M_{\rm s} \times M_{\rm r} \times M_{\rm s} \times M_{\rm co2} \times M_{\rm os}$ ($M_{\rm os}$, open/shorted, coupled lines, $M_{\rm co1/2}$ coupled lines with half-wavelength stubs, $M_{\rm s}$, side-coupled lines, $M_{\rm r}$, center two transmission lines), and the matrices of the coupled lines and stubs can be obtained from [13]. After *ABCD*-, Y- and S-parameter conversions, when $S_{21} = 0$, six transmission zeros can be obtained:

$$\theta_{tz1} = \pi/4, \quad \theta_{tz6} = 3\pi/4 \tag{1}$$

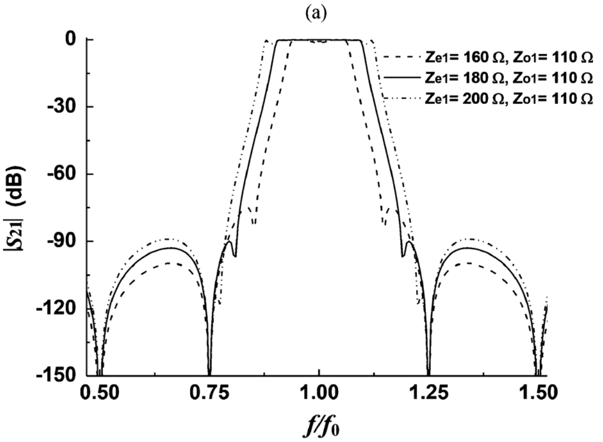
$$\theta_{tz2} = \arccos\frac{Z_{\rm e2} - Z_{\rm o2}}{Z_{\rm e2} + Z_{\rm o2}}, \quad \theta_{tz5} = \pi - \theta_{tz2} \tag{2}$$

$$\theta_{tz3} = \arccos\sqrt{\frac{Z_{\rm e1} + Z_{\rm o1} - 2Z_2}{Z_{\rm e1} + Z_{\rm o1} + 2Z_2}}, \quad \theta_{tz4} = \pi - \theta_{tz3}. \tag{3}$$

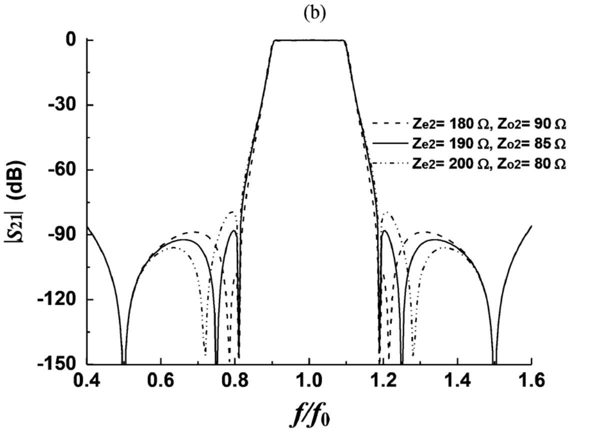
In addition, the transmission poles in the passband can be calculated when $S_{11} = 0$. When Z_0 is fixed, six roots for $S_{11} =$



(a)



(b)



(c)

Fig. 2. Simulated frequency responses of Fig. 1, (a) $Z_1 = 115\ \Omega$, $Z_2 = 120\ \Omega$, $Z_{\rm e1} = 180\ \Omega$, $Z_{\rm o1} = 110\ \Omega$, $Z_{\rm e2} = 190\ \Omega$, $Z_{\rm o2} = 85\ \Omega$, (b) $Z_1 = 115\ \Omega$, $Z_2 = 120\ \Omega$, $Z_{\rm e2} = 190\ \Omega$, $Z_{\rm o2} = 85\ \Omega$, (c) $Z_1 = 115\ \Omega$, $Z_2 = 120\ \Omega$, $Z_{\rm e1} = 180\ \Omega$, $Z_{\rm o1} = 110\ \Omega$ ($Z_{\rm o} = 50\ \Omega$).

0 can be found by properly choosing the relationships of Z_1, Z_2, $Z_{\rm e1}$, $Z_{\rm o1}$, $Z_{\rm e2}$, $Z_{\rm o2}$, and then six transmission poles in the passband can be achieved.

Fig. 2(a)–(c) show the simulated frequency responses of Fig. 1 (Ansoft Designer v3.0). Compared with the filter in [11], six transmission zeros $(f_{\rm tz1} = 0.5f_0, f_{\rm tz2}, f_{\rm tz3}, f_{\rm tz4}, f_{\rm tz5}, f_{\rm tz6} = 1.5f_0)$ can be realized by adding open stubs (Z_1) and the coupled lines $(Z_{\rm e2}, Z_{\rm o2})$, the passband-order can be also changed from fourth to sixth. In addition, the transmission zeros $(f_{\rm tz3}, f_{\rm tz4})$ created by the ring resonator do not change with the coupled lines $(Z_{\rm e2}, Z_{\rm o2})$, and the transmission zeros $(f_{\rm tz2}, f_{\rm tz5})$ created by the coupled lines do not change with the side-coupled lines $(Z_{\rm e1}, Z_{\rm o1})$. The six transmission poles imply the fact that $S_{11} = 0$ has six real solutions, when $Z_1, Z_2, Z_{\rm e1}, Z_{\rm o1}, Z_{\rm e2}, Z_{\rm o2}$ are properly selected.

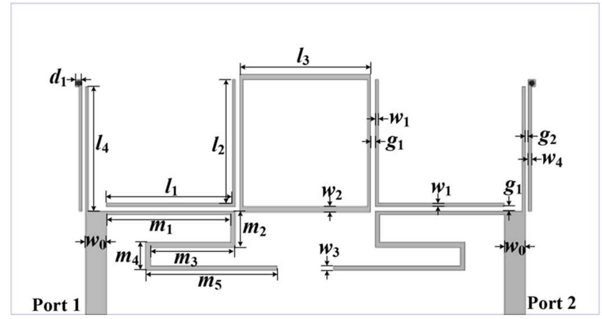


Fig. 3. Top view of the bandpass filter ($l_1 = 17$ mm, $l_2 = 16.9$ mm, $l_3 = 16.9$ mm, $l_4 = 16.7$ mm, $m_1 = 16.8$ mm, $m_2 = 4.6$ mm, $m_3 = 11.0$ mm, $m_4 = 3.6$ mm, $m_5 = 17$ mm, $w_0 = 2.7$ mm, $w_1 = 0.22$ mm, $w_2 = 0.42$ mm, $w_3 = 0.6$ mm, $w_4 = 0.27$ mm, $g_1 = 0.6$ mm, $g_2 = 0.29$ mm, $d_1 = 0.6$ mm, 70 mm × 40 mm, $1.06\lambda \times 0.61\lambda$).

Moreover, for a high selectivity bandpass filter, the concerned filter characteristics mainly include the 3 dB bandwidth, maximum $|S_{21}|$ ($T_{\rm stop}$, dB) in the stopband and the maximum in-band $|S_{11}|$ ($T_{\rm pass}$, dB), referring to the responses in Fig. 2(a). The 3 dB bandwidth is mainly determined by the characteristic impedance $Z_{\rm e1}, Z_{\rm o1}, Z_2$ (dual-mode ring resonator) [11]. The in-band balance of the filter can be adjusted by the characteristic impedance Z_1 (half-wavelength stubs) [13].

B. Proposed High Selectivity Bandpass Filter

To clarify the proposed filter design, the design procedures of the bandpass filter are summarized as follows:

1) Based on the (1)–(3), choose the desired center frequency f_0 of the bandpass filter, determine the six transmission zeros locations close to the passband;
2) Adjust the open loaded stubs (Z_1), and transmission lines (Z_2) to realize a sixth-order passband for the bandpass filter, choose the desired bandwidth for the filter (3 dB bandwidth greater than 20%, ($|S_{11}| < 15$ dB), out-of-band harmonic suppression ($|S_{21}| < -25$ dB);
3) Further optimize the values of $Z_{\rm e1}, Z_{\rm e1}$ to realize better in-band and out-of-band transmission characteristics of the bandpass filters, carry out full-wave electromagnetic simulation and dimension optimization in the commercial software of HFSS.

Referring to the above discussions and the simulated results in Section II.A the 3 dB bandwidth of the bandpass filter is chosen as 22%, and the final parameters for the filter circuit of Fig. 3 are: $Z_0 = 50\,\Omega$, $Z_1 = 115\,\Omega$, $Z_2 = 122\,\Omega$, $Z_{\rm e1} = 181\,\Omega$, $Z_{\rm o1} = 108\,\Omega$, $Z_{\rm e2} = 192\,\Omega$, $Z_{\rm o2} = 84\,\Omega$. The simulated results of the circuit for Fig. 3 are shown in Fig. 4, the insertion loss is less than 1.75 dB while the return loss is greater than 12 dB (2.85–3.5 GHz). Six transmission zeros are located at 1.45, 1.91, 2.36, 3.63, 3.78 and 4.15 GHz, respectively. Furthermore, over 25 dB upper stopband is obtained from 3.6 to 9.1 GHz $(2.87f_0)$. The group delay is less than 0.45 ns in the passband.

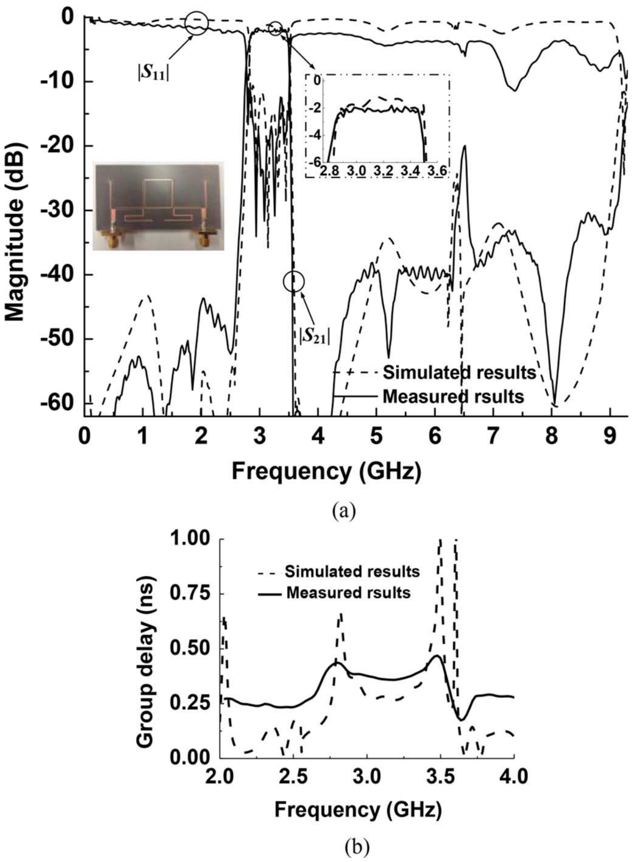


Fig. 4. Photograph, measured and simulated results of the bandpass filter. (a) Frequency responses, passband performance (b) group delay.

III. Measured Results and Discussions

Figs. 4(a)–(b) show the photograph and the measured results of the bandpass filter. Six transmission zeros are located at 1.31, 1.85, 2.51, 3.57, 4.01 and 4.13 GHz (3 dB bandwidth 20.6%, 2.84–3.49 GHz), respectively. The measured insertion loss is less than 2.2 dB, while the return loss is greater than 12.5 dB from 2.87 GHz to 3.39 GHz, the group delay is less than 0.60 ns in the passband. Furthermore, over 20 dB upper stopband is achieved from 3.57 to 9.21 GHz $(2.9f_0)$. The second harmonic around 6.45 GHz is mainly due to the desynchronization of the quarter-wavelength lines in the ring resonator [11].

For comparisons, Table I illustrates the measured results for some bandpass filter structures. Obviously, compared with the other filters [3]–[11], six transmission zeros close to the passband are realized with only a ring resonator and the upper stopband for the filter stretches up to $2.9f_0$, ($|S_{21}| < -20$ dB). Moreover, the bandwidth of the proposed filter can be further extended by using interdigital coupled lines as [5].

IV. Conclusion

In this letter, a high selectivity bandpass filter with six transmission zeros using only a ring resonator is proposed. Four transmission zeros can be adjusted conveniently by only changing the even/odd-mode of the open/shorted coupled line impedances. The proposed bandpass filter has advantages of high selectivity, high passband-order and wideband harmonic suppression. Good agreements between simulated and measured responses of the filter are demonstrated.

TABLE I
Comparisons of Measured Results for Some Bandpass Filters

Filter Structures	Transmission zeros, $\lvert S_{21}\rvert$ 0-$2f_0$, (f_0)	3-dB bandwidth	Numbers of ring resonator	Upper Stopband, $\lvert S_{21}\rvert$, dB
Ref. [3]	4 (5.6 GHz)	51.6%	2	< -18, ($1.5f_0$)
Ref. [4]	4 (4.0 GHz)	11.2%	2	< -20, ($1.6f_0$)
Ref. [5]	3 (4.0 GHz)	64.0%	1	< -25, ($2.0f_0$)
Ref. [6]	5 (3.0 GHz)	79.0%	1	< -25, ($2.6f_0$)
Ref. [7]	6 (5.0 GHz)	10.7%	2	< -20, ($1.4f_0$)
Ref. [9]	3 (6.8 GHz)	103%	1	< -20, ($2.4f_0$)
Ref. [10]	4 (7.7 GHz)	123%	1	< -15, ($2.4f_0$)
Ref. [11]	3 (2.0 GHz)	10.0%	1	< -20, ($2.8f_0$)
This work	**6 (3.2 GHz)**	**20.6%**	**1**	**< -20, ($2.9f_0$)**

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