Narrow-band Bandpass Filters with Improved Upper Stopband Using Open/Shorted Coupled Lines

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Abstract **–** Two transversal narrow-band bandpass filters with improved stopband based on open/shorted coupled lines and transversal signal-interaction concepts are proposed in this paper. By utilizing the stopband transmission characteristic of the open/shorted coupled lines, three transmission zeros can be easily achieved to suppress the second harmonic for the first bandpass filter. To further reduce the circuit size of the first filter, unequal open stubs and transmission lines are used for the second bandpass filter with six transmission zeros in the upper stopband. The transmission zeros near the passband can be adjusted conveniently by only changing the electrical length of the open/shorted stubs when the ratio of characteristic impedance is fixed. To verify the presented concepts, two prototypes ($\varepsilon_r = 2.65$, $h = 0.508$ mm, $tan\delta = 0.003$) with 3-dB fractional bandwidths (FBWs) of 4.3% (1.78-1.86 GHz), 2.8% (1.76-1.81 GHz) are designed and fabricated. Good agreements are observed for the theoretical and measured results, indicating good in-band filtering performances and high selectivity.

Index Terms **–** Bandpass filter, fractional bandwidth (FBW), narrowband, open/shorted coupled lines, transversal signal-interaction concepts.

I. INTRODUCTION

With the rapid growth of modern wireless communication systems [1]-[2], the bandpass filters with the features of planar structure, easy fabrication, low cost and easiness of integration into passive or active microwave components have attracted great attention. For conventional half-wavelength resonators bandpass filter, lowpass and bandstop networks are demanded to improve the rejection levels and harmonic suppression due to the unwanted periodic harmonics; however, the filter size and the passband insertion loss will enlarge [1].

In the past few years, different approaches have been applied to suppress harmonics of bandpass filters. Phase velocities compensation for the even- and odd-mode of the coupled lines using corrugated lines, substrate suspension and lumped-elements to remove the harmonics have been introduced in [3]-[4]. Stepped-impedance resonators with different characteristic impedance are capable of pushing the second harmonic to higher frequencies [5], cascaded different SIR structures with the same fundamental resonant and various high-order frequencies can be utilized to design high-order bandpass filters with wide upper stopband [6]-[8]. In addition, discriminating coupling, which blocks unwanted signals at certain frequency and allows the transmission of signals at other frequencies, can be used to suppress the harmonics without extra circuits [9]. Dual-behavior resonators (DBRs) with two stopband structures which bring two transmission zeros on either side of the passband can be used also to design high performance narrow-band bandpass filters [10], but low-pass structures and capacitive-coupled dual-behavior resonator are needed to suppress spurious resonances on both sides of the bandpass response [11].

Recently, wideband bandstop/bandpass filters based on transversal signal-interaction concepts have drawn a lot of attention [12]-[15]. By introducing intentionally a passband constructive interference and out-of-band signal energy cancellations to produce power transmission zeros, high-selectivity filtering responses and harmonic suppression can be achieved in this kind of filter structures. However, little research has described the application of transversal signal-interaction concepts in the high performance narrow-band bandpass filters. In this paper, two transversal narrow-band bandpass filters with improved upper stopband based on open/shorted coupled lines and transversal signal-interaction concepts are proposed. Three transmission zeros can be easily realized by the two transmission paths consisting of two open/shorted coupled lines for the two narrowband bandpass filters, another three more transmission zeros are realized for the second bandpass filter with two asymmetric transmission paths. The transmission zeros for the two transversal narrowband bandpass filters can be adjusted conveniently by changing the electrical length of the open/shorted stubs when the ratio of characteristic impedance is fixed. Detailed theoretical design, simulation and experimental results are demonstrated and discussed. The organization and

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framework of this paper should be given here.

II. ANALYSIS OF PROPOSED NARROW-BAND FILTERS

A. Bandpass filter with three zeros in upper stopband

Figure 1 (a) shows the first proposed bandpass filter with three zeros in upper stopband. Similar as the wideband filters in [12]-[15], two similar transmission paths are introduced to realize the signal transmission from Port 1 to Port 2. The characteristic impedance of the two pairs of open/shorted stubs is Z_2 (electrical length θ_1, even/odd-mode characteristic impedance Z_{oe}, Z_{oo}) with two attached transmission lines (characteristic impedance Z_1, electrical length θ_1). For calculation simplicity, $Z_1 = Z_2$ are chosen, and the input admittance Y_{in1} of Fig. 1 (b) can be illustrated as [1]:

$$Y_{in1} = -j\cot(\theta_1+\theta_2)/Z_1 + j\tan\theta_2/Z_1. \tag{1}$$

As discussed in [6], [16], the external quality factor Q_{e1} of Fig. 1 (b) can be calculated as:

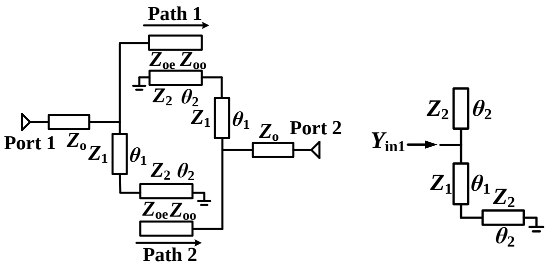
$$Q_{e1} = R_{L1}\frac{\omega_0}{2}\left.\frac{dY_{in1}}{d\omega}\right|_{\omega_0}, \tag{2}$$

where R_{L1} is the load impedance for the open/shorted stubs, ω_0 is the operation frequency, and after further calculation, Q_{e1} can be illustrated as:

$$Q_{e1} = 0.5R_{L1}[(\theta_1+\theta_2)\csc^2(\theta_1+\theta_2)/Z_1 + \theta_2\sec^2\theta_2/Z_1]. \tag{3}$$

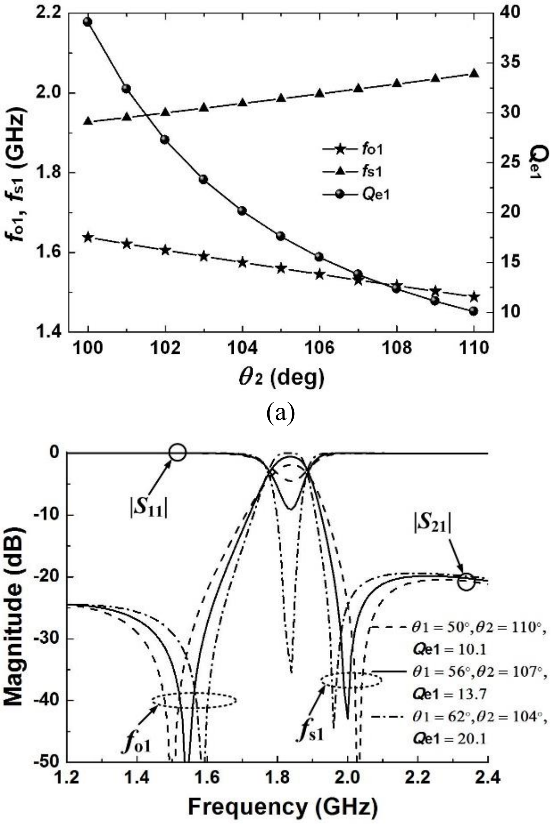
When $Y_{in1} = 0$, the resonant condition of open/shorted stubs can be obtained; meanwhile the external quality factor Q_{e1} of the bandpass filter can be selected from the required value of filter specification, then the two unknown variables θ_1 and θ_2 can be solved when the ratio of Z_1/Z_2 are fixed. The open/shorted stubs using the conditions (1) = 0 and (2) to solve the two remnant unknown variables (θ_1, θ_2) is similar to the method used in [16], which can avoid the use of additional impedance transformers. The transmission zeros and the external quality factor Q_{e1} versus θ_2 and the simulated frequency responses of the filter are shown in Figs. 2 (a)-(c). We may notice that, each desired transmission zero frequency of the open/shorted stubs is equal to quarter/half-wavelength, respectively [1], and the two transmission zeros created by the open/shorted stubs can be freely chosen to locate in both sides of the passband. Besides the transmission zeros (f_{01}, f_{s1}) of the open/shorted stubs, the transmission zero ($2f_{01}$) created by the bandstop transmission characteristic of the open/shorted coupled lines [1] and the transmission zeros ($2f_{s1}$) of the shorted stubs can be also used to further improve the upper stopband of the narrow-band bandpass filter, and the frequencies of four transmission zeros decrease as θ_1, θ_2 increase.

Moreover, the desired external quality factor Q_{e1} of the filter can be obtained by changing the electrical length θ_2 of the open stub when $Z_1 = Z_2$. If we want to adjust the frequencies of the transmission zeros (f_{01}, f_{s1}) with similar Q_{e1} value for the narrow-band bandpass filter, the R_{L1} value ($Z_1 \neq Z_2$) can be altered correspondingly to keep the Q_{e1} value unchanged, if the R_{L1} does not equal to 50 Ω. In addition, the quarter-wavelength transformer should be employed to perform as the impedance transformation, as discussed in [6]. To further reduce the circuit size and improve the harmonic suppression of the narrow-band bandpass filter with three transmission zeros in upper stopband, a narrow-band bandpass filter with six transmission zeros in upper stopband will be proposed and investigated next.



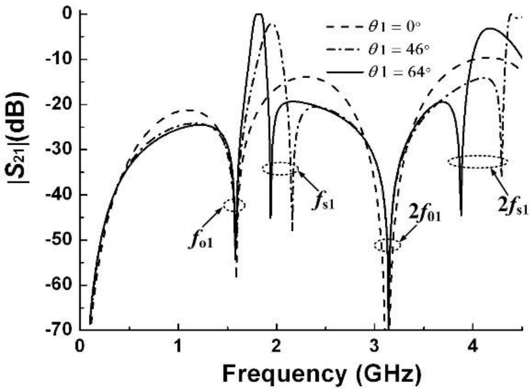
(a) (b)

Fig. 1. (a) Bandpass filter with three transmission zeros in upper stopband, and (b) the input admittance of the open/shorted stubs.



(a)

(b)



(c)

Fig. 2. (a) Transmission zeros and external quality factor Q_{e1} versus θ_2, θ_1 = 270°-2θ_2, (b) simulated frequency responses of the filter, and (c) simulated frequency responses versus θ_1, θ_2= 103°. (Z_o = 50 Ω, $Z_1 = Z_2$ = 100 Ω, Z_{oe} = 141 Ω, Z_{oo} = 74 Ω, f_0 = 1.82 GHz).

B. Bandpass filter with six zeros in upper stopband

The bandpass filter with six transmission zeros in the upper stopband is shown in Fig. 3 (a). Different from the bandpass filter with three transmission zeros in the upper stopband, there is only a pair of open/shorted stubs in Path 1, the transmission line with characteristic impedance Z_1 and electrical length θ_1 has been removed for Path 1; the Path 2 is same as the filter of Fig. 1 (a), and a shunt-connected stub (characteristic impedance Z_3, electrical length θ_3) are connected in Port 2. As discussed in *Part A*, $Z_1 = Z_2$ are chosen for simplicity, and the input admittance Y_{in21}/Y_{in22} of Fig. 3 (b) can be illustrated as:

$$Y_{in21} = -j\cot(\theta_1+\theta_2)/Z_1 + j\tan\theta_2/Z_1, \quad (4)$$

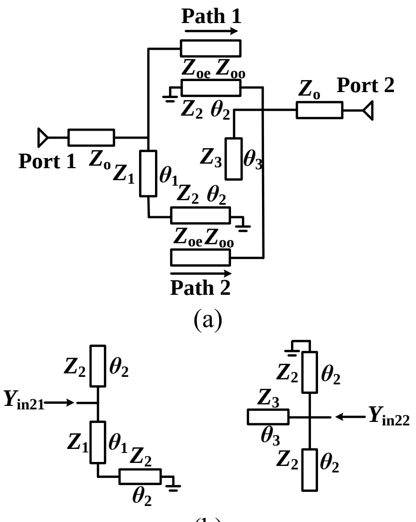
$$Y_{in22} = -j\cot\theta_2/Z_1 + j\tan\theta_2/Z_1 + j\tan\theta_3/Z_3. \quad (5)$$

The external quality factor Q_{e21}/Q_{e22} of Fig. 3 (b) can be calculated as:

$$Q_{e21} = 0.5R_{L21}[(\theta_1+\theta_2)\csc^2(\theta_1+\theta_2)/Z_1 + \theta_2\sec^2\theta_2/Z_1], \quad (6)$$

$$Q_{e22} = 0.5R_{L22}[(\theta_2\csc^2\theta_2/Z_1 + \theta_2\sec^2\theta_2/Z_1 + \theta_3\sec^2\theta_3/Z_3]. \quad (7)$$

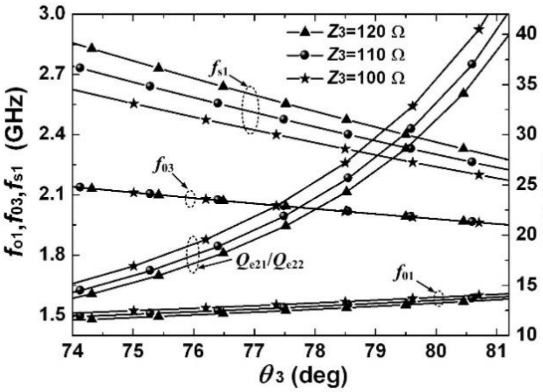
When $Y_{in21} = Y_{in22} = 0$, the resonance condition of open/shorted stubs of Fig. 3 (b) can be also obtained, and the external quality factor Q_{e21} should be equal to Q_{e22} to meet the required value of filter specification, and then the three unknown variables θ_1, θ_2 and θ_3 can be solved when the ratio of Z_1/Z_2, Z_1/Z_3 are fixed. In addition, it can be deduced that the shunt-connected stub θ_3 is a requirement condition for the Equation (5) to have real roots. The transmission zeros and the external quality factor Q_{e21}/Q_{e22} versus θ_3 and the simulated frequency responses of the filter with six transmission zeros in upper stopband are shown in Figs. 4 (a)-(c). As the filter originally has three transmission zeros in upper stopband, besides the transmission zeros (f_{01}, f_{03}, f_{s1}) of the open/shorted stubs (θ_1, θ_2, θ_3), the transmission zero ($2f_{01}$, $3f_{01}$) created by the bandstop transmission characteristic of the open/shorted coupled lines [1] and the transmission zeros ($2f_{s1}$) of the shorted stubs can be also used to improve the upper stopband of the narrow-band bandpass filter. In addition, the simulated transmission coefficients of the two paths at the frequency of f_{tsc} (4.18 GHz, tsc-transversal signal-interaction concepts) are 0.13∠81.8° and 0.13∠-98.7°, respectively. Thus, the signals transmitted from the two paths have the same magnitude but out-of-phase and are thus cancelled out, resulting in the generation of f_{tsc} [14]-[15]. Moreover, in Fig. 4 (b), for same external quality factor Q_{e21}/Q_{e22}, the passband responses are nearly unchanged and the locations of the transmission zeros (f_{01}, f_{03}, f_{s1}) for the open/shorted stubs (θ_1, θ_2, θ_3) can be freely chosen to locate in either both of the stopbands, leading to a quasi-elliptic function that improves the passband and out-of-band performances for the filter.



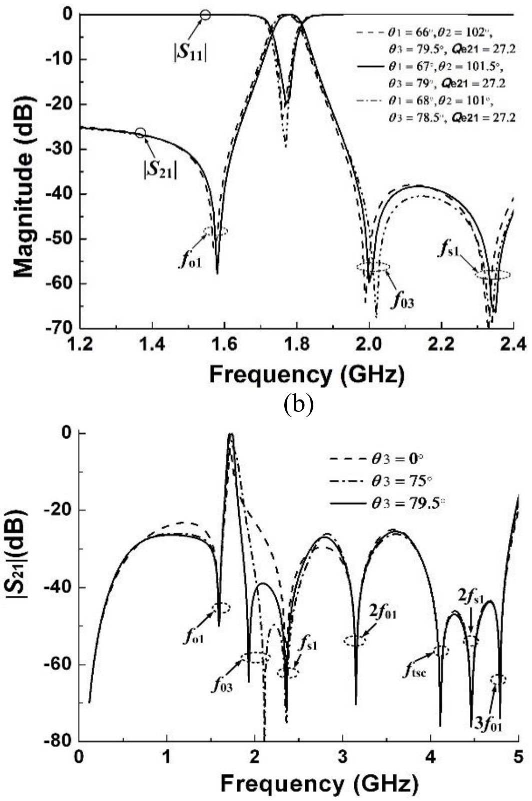
(a)

(b)

Fig. 3. (a) Bandpass filter with six zeros in upper stopband, and (b) the input admittance of the open/shorted stubs.



(a)



(b)

(c)

Fig. 4. (a) Transmission zeros and external quality factor Q_{e21}/Q_{e22} versus θ_3, $\theta_1 = 270°\text{-}2\theta_2$, (b) simulated frequency responses of the filter for same Q_{e21}/Q_{e22}, and (c) simulated frequency responses versus θ_3, θ_1=66°, θ_2=102°. (Z_o= 50 Ω, $Z_1 = Z_2$ = 100 Ω, Z_{oe} = 127 Ω, Z_{oo} = 85 Ω, f_0 = 1.76 GHz).

III. FILTERS DESIGN AND MEASURED RESULTS

A. Design procedures

In order to demonstrate the proposed concepts, two experimental Chebyshev bandpass filters with three and six transmission zeros in upper stopband are implemented with center frequency of 1.82 GHz and 1.76 GHz, fraction bandwidths of 4.2% and 3.1% and ripple of 0.1 dB. Based on the required responses, the lumped element values of the second-order prototypes filter are selected to be: $g_0 = 1$, $g_1 = 0.8431$, $g_2 = 0.6220$, $g_3 = 1.3554$. The required coupling coefficient and external quality factor can be obtained based on [1]:

$$Q_e = \frac{g_0 g_1}{FBW}, \quad k = \frac{FBW}{\sqrt{g_1 g_2}}. \tag{8}$$

It can be calculated that Q_{e1} = 20.1, k_1 = 0.058; Q_{e21} = Q_{e22} = 27.2, k_2 = 0.043. The Q_e factors and the coupling coefficients are extracted based on:

$$Q_e = \frac{f_0}{\Delta f_{\pm 90°}}, \quad k = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2}, \tag{9}$$

where f_0 is resonant frequency, and $\Delta f_{\pm 90°}$ is the bandwidth over which the phase shifts ±90º with respect to the absolute phase at f_0; f_1 and f_2 are the two resonant frequencies of the open/shorted coupled lines. Figure 5 shows the extracted k at f_2 against the gap (g_1) of the open/shorted coupled lines.

Based on the above discussion and the theoretical analysis in *Section II*, the final parameters for the two bandpass filters are: Z_0 = 50 Ω, Z_1 = 100 Ω, Z_2 = 100 Ω, θ_1 = 62°, θ_2 = 104°, Q_{e1} = 20.1, k_1 = 0.058, Z_{oe} = 137 Ω, Z_{oo} = 73 Ω, f_0 = 1.82 GHz; Z_0 = 50 Ω, Z_1 = 100 Ω, Z_2 = 100 Ω, Z_3 = 120 Ω, θ_1 = 66°, θ_2 = 102°, θ_3 = 79.5°, Q_{e21} = Q_{e22} = 27.2, k_2 = 0.043, Z_{oe} = 127 Ω, Z_{oo} = 85 Ω, f_0 = 1.76 GHz. The final structure parameters for two bandpass filters shown in Figs. 6 (a)-(b) are: l_1 = 20.9 mm, l_2 = 13.4 mm, l_3 = 20.4 mm, l_4 = 12.6 mm, l_5 = 19.9 mm, w_0 = 1.37 mm, w_1 = 0.35 mm, d = 0.5 mm, g_1 = 0.20 mm, 52 mm × 34 mm, ε_r = 2.65, h = 0.5 mm, tan δ = 0.003; l_1 = 10.3 mm, l_2 = 23.3 mm, l_3 = 12.35 mm, l_4 = 22.3 mm, l_5 = 10.95 mm, l_6 = 22.65 mm, l_7 = 20.95 mm, m_1 = 2.5 mm, m_2 = 3.3 mm, m_3 = 10.2 mm, m_4 = 10.0 mm, w_0 = 1.37 mm, w_1 = 0.35 mm, w_2 = 0.25 mm, g_1 = 0.40 mm, 42 mm × 40 mm, ε_r = 2.65, h = 0.5 mm, tan δ = 0.003.

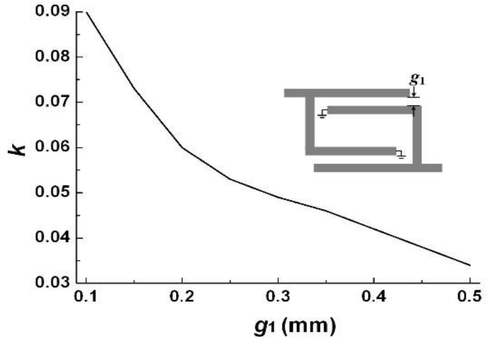
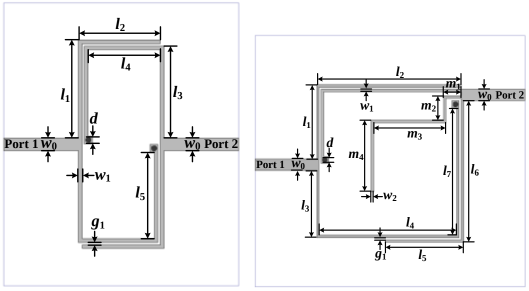


Fig. 5. Variation of k against the coupling gap (g_1) of the open/shorted coupled lines.



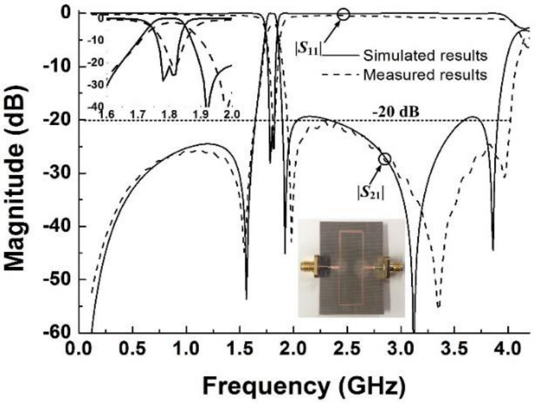
(a) (b)

Fig. 6. Geometries of the two narrow bandpass filters: (a) three zeros in upper stopband, and (b) six zeros in upper stopband.

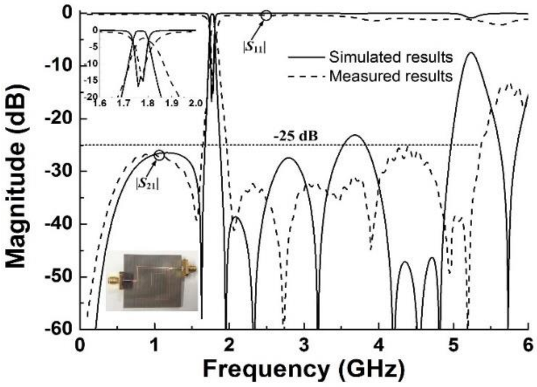
B. Measured and simulated results

The photographs, measured and simulated results of the two bandpass filters are shown in Fig. 7. For the filter with three transmission zeros in upper stopband, four measured zeros are located at 1.55, 1.99, 3.36 and 3.98 GHz, respectively, the 3-dB bandwidth of the bandpass filter is approximately 4.3% (1.78-1.86 GHz) with 20-dB upper stopband from 1.96 to 4.85 GHz (2.66f_0); for the filter with six transmission zeros in upper stopband, seven measured transmission zeros are located at 1.56, 2.0, 2.73, 3.46, 3.89, 4.95 and 5.2 GHz, respectively, a passband with return loss greater than 12 dB is realized (3-dB fractional bandwidth is approximately 2.8% (1.76-1.81 GHz)) with 25-dB upper stopband from 1.97 to 5.4 GHz (3.07f_0). Compared with the bandpass filter with three zeros in upper stopband, the circuit size has been reduced and the harmonic suppression has been much improved. However, the in-band insertion loss for the second bandpass filter is a little big. Some better dielectric substrate such as Rogers 5880 with $\varepsilon_r = 2.65$, $h = 0.508$ mm, and $tan\delta = 0.0009$ can be chosen to realize higher-order bandpass filter with low insertion loss. In addition, the slight frequency discrepancies of the transmission zeros in the upper stopband and larger insertion loss for the passband between the measured and simulated results are mainly caused by the imperfect soldering skill of the shorted stubs and folded transmission line of the filter, and the even and odd mode phase velocities of the microstrip coupled line also affect the positioning of the transmission zeros of the filters; some slots located in the shorted/coupled lines can be considered to extend the electrical path of the odd mode, and the effective phase velocity of odd mode will be reduced [17].

For the purpose of comparison, Table 1 illustrates the measured results for some bandpass filters. Compared with other bandpass filters [4]-[16], the core circuit size of the filter with six zeros in the upper stopband is very compact, which is only $0.040\lambda^2_0$, and seven transmission zeros with wide upper stopband ($3.07f_0$, $|S_{21}| > 25$ dB) are realized for the narrow bandpass filter. Moreover, the upper stopband of the two proposed filters can be further extended by using stepped impedance resonator stubs as [18].



(a)



(b)

Fig. 7. Photographs, measured and simulated results of the two narrow bandpass filters: (a) three zeros in upper stopband, and (b) six zeros in upper stopband.

Table 1: Comparisons of some bandpass filters

Filters	TZs, (f_0)	3-dB Bandwidth	In-band $\|S_{11}\|$, dB	Circuit Size, (λ^2_0)	Upper Stopband, $\|S_{21}\|$, dB
Ref. [4]	3 (1.57 GHz)	1.80%	> 15.0	0.3*0.22	> 20 (2.67f_0)
Ref. [10]	6 (5.00 GHz)	4.50%	> 15.0	0.8*0.50	> 20 (2.60f_0)
Ref. [16]	8 (2.00 GHz)	6.00%	> 15.0	0.5*0.25	> 27 (2.88f_0)
This work	4 (1.82 GHz)	4.30%	> 15.0	0.23*0.2	> 20 (2.66f_0)
	7 (1.78 GHz)	2.80%	> 13.0	0.2*0.2	> 25 (3.07f_0)

IV. CONCLUSION

In this paper, two transversal high selectivity narrow-band bandpass filters with improved upper stopband using open/shorted couple lines based on transversal signal-interaction concepts are proposed. Four and seven transmission zeros can be adjusted conveniently by only changing the electrical length of the open/shorted stubs when the ratio of characteristic impedance of the stubs are fixed. The proposed bandpass filters have advantages of compact effective circuit size, simpler design theory and wideband harmonic suppression. Good agreements between simulated and measured responses of the filters are demonstrated, which will make the proposed filters suitable for wireless applications.

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