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WIDEBAND BANDPASS FILTERS USING PARALLEL-COUPLED SIRs WITH WIDE SPURIOUS SUPPRRESSION

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Abstract—This paper proposes parallel-coupled stepped impedance resonators (SIRs) used for wideband bandpass filters with reduced size and improved spurious response suppression in out-of-band. The filter design concept is demonstrated by both two- and four-parallel coupled line resonator structures with the same fundamental frequency (f_0) of 6.5 GHz. The first bandpass filter has been designed using two resonators with $\lambda/2$ slot and embedded slot feeds for spurious response suppression at $2f_0$ and $3f_0$, respectively. The measured insertion loss is around 0.3 dB and the operation band is from 4.4 to 9.2 GHz (FBW = 73.8%). For the second bandpass filter, the embedded slot feeds and additional loaded open-stubs have been utilized to improve the wide spurious response suppression and sharp skirt characteristic in the passband. The measured passband of frequency response is from 4.2 to 8.6 GHz (FBW = 67.7%). The insertion loss of passband is lesser than 0.25 dB and the return loss is better than 15 dB. The filter designs are described in details. The simulated and experimental results are demonstrated and discussed.

1. INTRODUCTION

Bandpass filters are essentially required in radio frequency (RF) front end equipment of wireless communication systems. However, high performances with compact size and high suppression of spurious response are also necessarily demanded for several communication systems. Planar filters are currently very popular because they can

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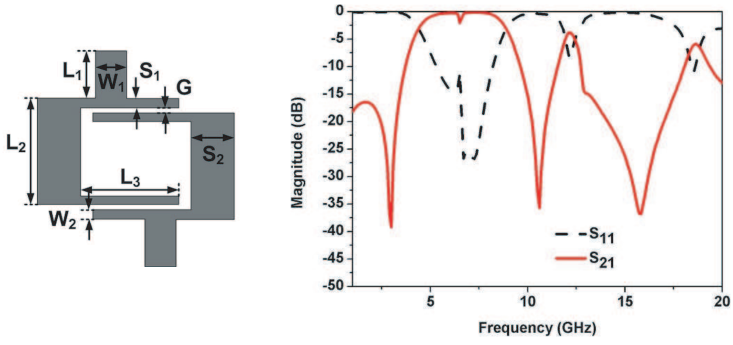
be built on microstrip structures with small size and low fabrication cost suitable for commercial applications. Several spurious response suppression techniques have been reported in recent years. The parallel-coupled line structures are most popular for building up bandpass filters [1]. The parallel-coupled lines with open-stubs for harmonic suppression improvement have been also proposed [2]. The filter used the pseudo-interdigital stepped impedance resonators for improving the skirt characteristic and compact size has been reported [3], but the spurious response in the out-of-band cannot be suppressed. Moreover, asymmetrical stepped impedance resonator (ASIR) structure with $\lambda/4$ tuning stubs can also reduce the size and provide the transmission zero [4]. In [5], microstrip stepped impedance resonator loaded with triangular and rectangular microstrips at both ends has been designed for reduced size and improved stopband characteristics, but the insertion loss level was considerably high. Stepped impedance hairpin resonators with asymmetric capacitive-loaded coupled lines have been reported [6], which the suppression level only about 20 dB was obtained. Aperture-backed microstrip-line stepped impedance resonators have been developed and demonstrated for a good improvement in out-of-band characteristics as well [7], but the necessary position alignment between the top and bottom parts of the filter causes some problems and may be difficult to fabricate. Several papers presented many ways to improve the rejection bands. Even though a folded SIR technique has been widely used to design the compact filters with wide stopband characteristics, the filter passband insertion losses are normally high [8–10]. In [11–13], a compact UWB-BPF with narrow notched band has been proposed by using embedded $\lambda/4$ slot with stubs to reject any undesired existing radio signal. Recently, the method of determining feed positions in the half-wavelength coupled SIR bandpass filters is proposed by using the concept of impedance matching [14]. In [15–17], SIRs with different dimensions of parallel-coupled lines and transmission zeros tuning to improve the rejection of the filters have been investigated.

This paper uses the concept of SIR to demonstrate the wideband bandpass filter design for wide spurious suppression. The first filter employs a two-resonator parallel-coupled line structure with slots and embedded open-stubs feeds. The second one is a four-resonator parallel-coupled line bandpass filter with embedded slot feeds and loaded open-stubs. The proposed wideband bandpass filters have compact sizes and improved spurious response suppression. The proposed two-resonator parallel-coupled line filter will be designed, resulting in the filter prototypes and measurement results as given in Section 2. In Section 3, details of the four-resonator filter are demonstrated. Finally, a brief discussion and conclusion is given in Section 4.

2. A TWO-RESONATOR PARALLEL-COUPLED LINE BANDPASS FILTER

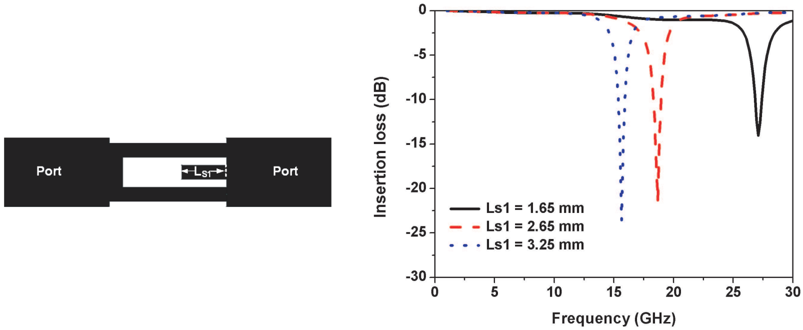
Figure 1(a) shows a conventional filter structure as proposed in [3]. It produces the ultra-wideband response by using pseudo-interdigital stepped impedance resonators. This filter obtains the improved skirt characteristics and very compact size. The conventional filter on a substrate with a permittivity of 10.6 and a thickness of 0.768 mm has been studied. The strip widths S_1 and S_2 of the resonator are very small which are around 0.3 mm and 1.44 mm, respectively, and also the gap G is 0.1 mm for a tight coupling between the resonators. Even though the filter has a very compact size and skirt improvement, the strip widths and gap are very small and may be very difficult for fabrication. The designed filter with its parameters $L_1 = 4$ mm, $L_2 = 8.7$ mm, $L_3 = 8.1$ mm, $W_1 = 2.5$ mm, and $W_2 = 0.7$ mm is shown in Fig. 1(a). By using IE3D software, it has been found that the out-of-band response includes harmonics as shown in Fig. 1(b).

The technique which involves embedding open-stubs within the filter circuit in order to reject any undesired existing radio signal as proposed in [11] has been applied for this work. The $\lambda/4$ open-stub (at $3f_0$) is now embedded into the feed port as shown in Fig. 2(a) to generate a narrow notch in out-of-band response useful for spurious response suppression. The notched frequency can be varied by



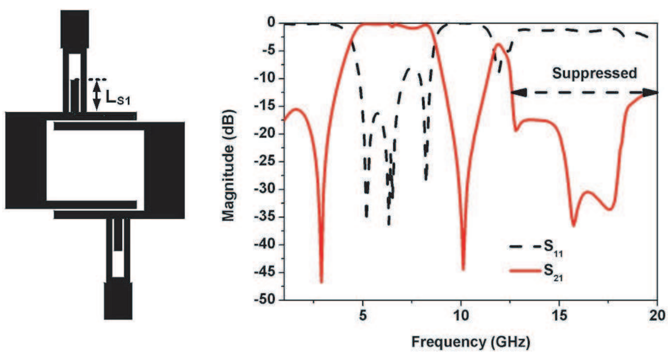
(a) (b)

Figure 1. (a) Configuration of the conventional filter with $S_1 = 0.3$ mm, $S_2 = 1.44$ mm, $G = 0.1$ mm and (b) frequency response of the conventional filter from the IE3D program.



(a) (b)

Figure 2. (a) Configuration of embedded open-stub and (b) frequency response when varying L_{S1}.



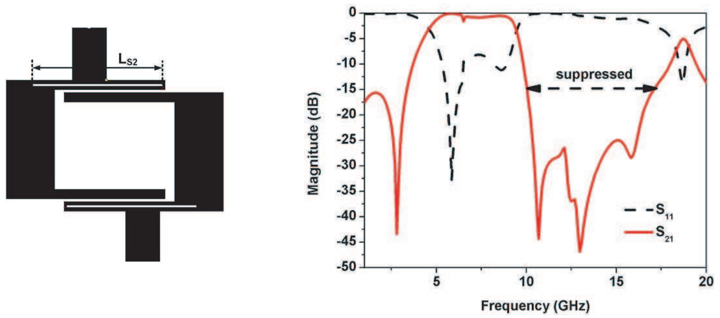
(a) (b)

Figure 3. (a) Layout of two-resonator filter with embedded open-stub and (b) frequency response.

changing the $\lambda/4$ open-stub length, L_{S1}. Fig. 2(b) shows the notched frequency response when varying L_{s1} while the stub width is 0.7 mm by using the IE3D simulation program.

Figure 3(a) shows the filter with proposed embedded open-stubs at both input and output ports for the spurious harmonics suppression. It can be clearly seen that the embedded open-stubs can suppress the spurious at around $3f_0$ as shown in Fig. 3(b). However, the spurious frequency response at around $2f_0$ is still appeared. To eliminate this spurious, the $\lambda/2$ slot (at $2f_0$) has been proposed as shown in Fig. 4(a).

The substrate of Arlon/Diclad 880 with relative dielectric constant of 2.17 and thickness of 0.768 mm has been employed to design the



(a) (b)

Figure 4. (a) Layout of two-resonator filter with slot and (b) frequency response.

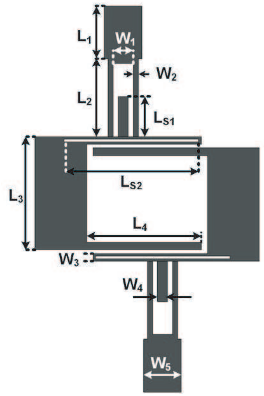
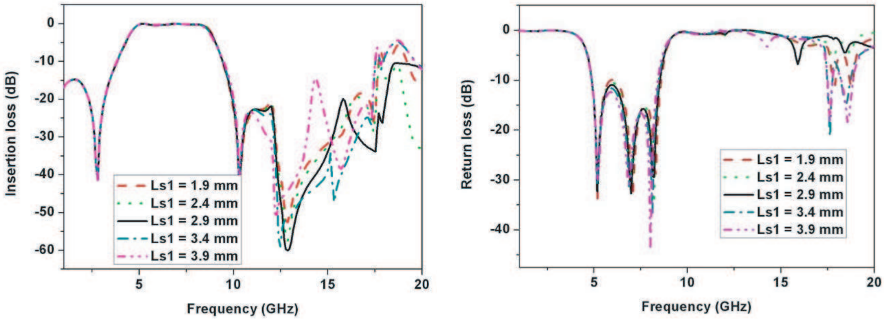


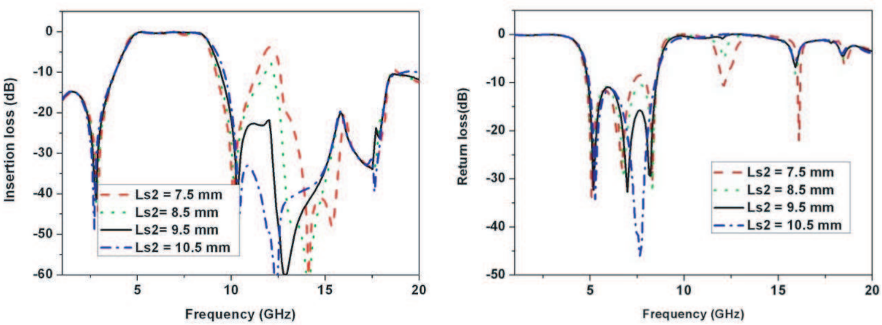
Figure 5. The proposed SIR filter with $L_1 = 4\,\text{mm}$, $L_2 = 5.8\,\text{mm}$, $L_3 = 8.7\,\text{mm}$, $L_4 = 8.1\,\text{mm}$, $W_1 = 1.1\,\text{mm}$, $W_2 = 0.5\,\text{mm}$, $W_3 = 0.7\,\text{mm}$, $W_4 = 0.7\,\text{mm}$, $W_5 = 2.5\,\text{mm}$, and slot width of $L_{s2} = 0.15\,\text{mm}$.

proposed filter. The IE3D program has been used to simulate the filter with $\lambda/2$ slot, resulting in the frequency response as shown in Fig. 4(b). It has been found that the spurious response at $2f_0$ is now eliminated. Finally, the proposed filter with embedded stubs at ports and slots has been designed, as shown in Fig. 5. The significant parameters affected to the spurious suppression are the embedded open-stubs, L_{s1}, and the slot at the high impedance arm, L_{s2}. Then the slot L_{s1} is varied ($L_{s1} = 1.9$, 2.4, 2.9, 3.4 and 3.9 mm), resulting in the frequency responses as shown in Figs. 6(a) and (b). We found that the suitable length of L_{s1} is around 2.9 mm for superior spurious suppression at $3f_0$.



(a) (b)

Figure 6. Simulated frequency responses when varying L_{S1} (a) insertion loss and (b) return loss.



(a) (b)

Figure 7. Simulated frequency responses when varying L_{S2} (a) insertion loss and (b) return loss.

Figs. 7(a) and (b) show the frequency responses, when the parameter L_{s2} is varied (L_{s2} = 7.5, 8.5, 9.5 and 10.5 mm) while the slot L_{s1} is fixed to be 2.9 mm. It can be observed that the spurious response suppression at $2f_0$ or around 12 GHz is better than 20 dB when the slot $L_{s2} = 9.5$ mm and the resonator slot width of 0.15 mm.

Figure 8 shows the current distributions at the frequencies of $2f_0$ and $3f_0$. We found that at the $2f_0$ the current densities are around the resonator slot at input port, resulting in no current passing through the output port. Therefore, the spurious response can be suppressed at $2f_0$. It is also clearly seen that the spurious response can be suppressed at $3f_0$ due to the effect of embedded open-stub feeds.

Figure 9 shows a photograph of the fabricated filter with overall

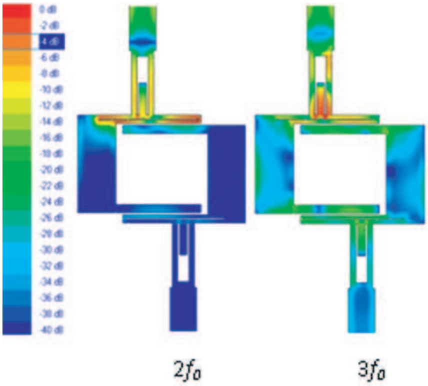


Figure 8. Current densities of the filter circuit at the $2f_0$ and $3f_0$.

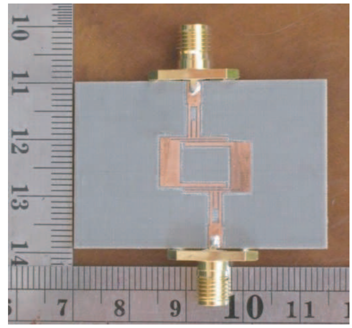
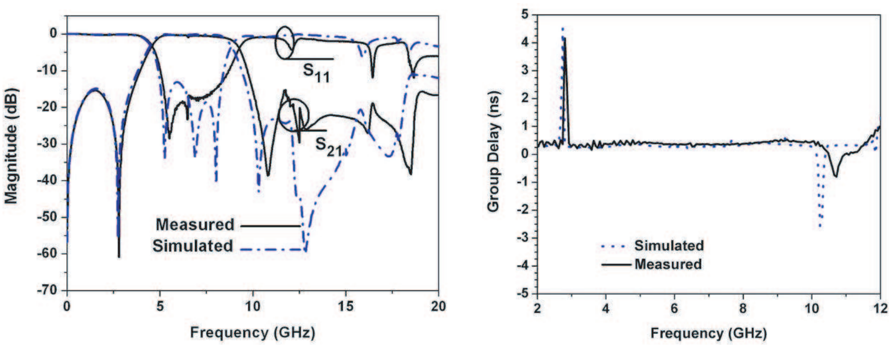


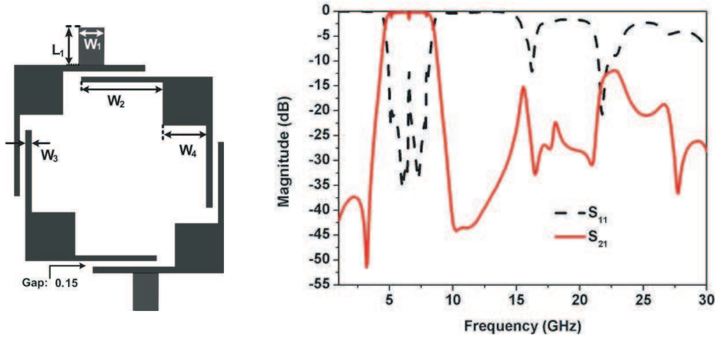
Figure 9. Photograph of the fabricated filter.



(a) (b)

Figure 10. Comparison of measured and simulated responses of (a) S_{11} and S_{21} and (b) group delay.

size of the filter of 29 mm × 16 mm. The measured and simulated results of the proposed filter at the center frequency of 6.5 GHz are illustrated in Fig. 10(a). The measured insertion loss is around 0.3 dB and the operation band is from 4.4 to 9.2 GHz (FBW = 73.8%). The transmission zeros are at 2.8 GHz for the lower passband skirt and 10.6 GHz for the higher passband skirt. The filter can suppress the harmonic signals more than 16 dB and extend to 20 GHz ($3f_0$). The group delay of the filter has been measured comparing with the simulation as shown in Fig. 10(b), which slightly variation between 0.3 to 0.4 ns in the passband has been obtained.



(a) (b)

Figure 11. (a) Layout of the four-resonator bandpass filter with normal feed port and (b) frequency responses.

3. A FOUR-RESONATOR PARALLEL-COUPLED LINE BANDPASS FILTER

For the two-resonator filter, it can be observed that even though the filter can suppress the higher spurious response, a wide-skirt (not sharp) response has been obtained. Hence, the four-resonator SIRs with cross coupling structure are utilized for improving skirt shape factor. The four-resonator filter with normal port feeds is shown in Fig. 11(a). The substrate of Arlon/Diclad 880 with relative dielectric constant of 2.17 and thickness of 0.768 mm has been used. By using the IE3D simulation program [19], we observed that the shape factor has been improved in passband as shown in Fig. 11(b), but the out-of-band has spurious responses at $2f_0$ and $4f_0$. For retrieving this problem, the new filter design is also proposed. To suppress spurious responses at $2f_0$ and $4f_0$ the embedded open-stub ports have been used. Also, the loaded open-stubs have been added at the ports to eliminate the spurious responses at $2f_0$.

The proposed filter has been designed. The same substrate of Arlon/Diclad 880 is employed for construction of the second wideband bandpass filter. The IE3D software has been then used to design and optimize the proposed filter. The dimensions of the filter are shown in Fig. 12(a): $L_1 = 4$ mm, $L_2 = 4.3$ mm, $L_3 = 2.2$ mm, $L_4 = 3.15$ mm, $L_5 = 1.65$ mm, $W_1 = 2.5$ mm, $W_2 = 8.5$ mm, $W_3 = 0.6$ mm, and $W_4 = 4.5$ mm. The filter could be synthesized by using a method based on the knowledge of the coupling coefficients of three basic coupling structures, as described in [20, 21]. There are four coupling coefficients to be determined, namely K_{12}, K_{23}, K_{34} and K_{14}, where

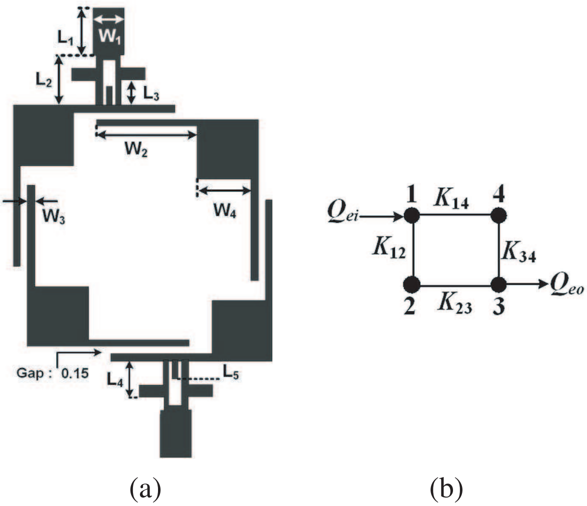


Figure 12. (a) Configurations of the proposed SIR filter with $L_1 = 4\,\text{mm}$, $L_2 = 4.3\,\text{mm}$, $L_3 = 2.2\,\text{mm}$, $L_4 = 3.15\,\text{mm}$, $L_5 = 1.65\,\text{mm}$, $W_1 = 2.5\,\text{mm}$, $W_2 = 8.5\,\text{mm}$, $W_3 = 0.6\,\text{mm}$, and $W_4 = 4.5\,\text{mm}$ and (b) coupling coefficient direction.

K_{ij} specifies the coupling between the resonators, i and j. All coupling coefficients are identical as the structure shown in Fig. 12(b). Let Q_{ei} and Q_{eo} are the external quality factors of the input and output resonators, respectively. The element values g_i for the given three poles Chebyschev lowpass prototype are $g_0 = g_4 = 1$, $g_1 = g_3 = 1.0316$ and $g_2 = 1.1474$. The external quality factor and the coupling coefficients of the proposed filter can be found to be $Q_{ei} = Q_{eo} = 1.6948$ and $K = 0.5809$, respectively. The coupling gap of 0.15 mm is obtained to satisfy the required coupling coefficients between resonators.

More clearly, Fig. 13(a) illustrates simulated frequency responses between the structures with and without the loaded open-stubs at the port feeds. It is found that the structure without the loaded open-stubs at the port feeds has the spurious responses at around 15 GHz ($2f_0$) and 23 ($4f_0$) GHz, respectively. When putting the loaded open-stubs, the spurious responses at both frequencies have been suppressed. This can be explained by the current distributions as shown in Fig. 13(b); without loaded open-stubs, the current densities at the spurious frequencies can pass through the next port. It is different when putting the loaded open-stubs; the current densities at the spurious frequencies are around the open-stubs of the port feeds as shown in Fig. 13(c). Therefore, the technique to suppress the

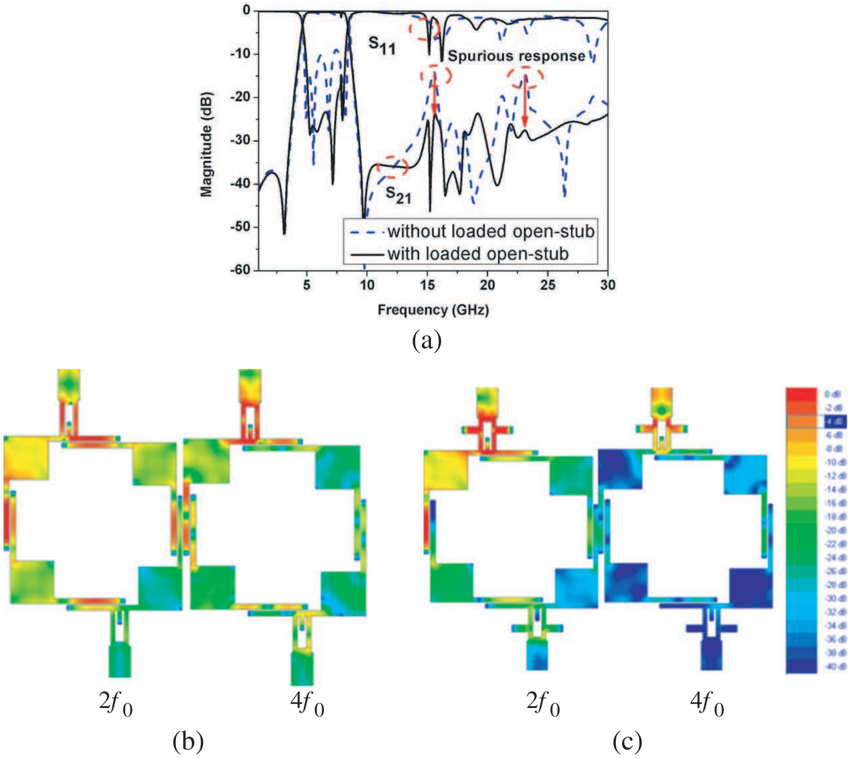


Figure 13. (a) The frequency response of the structure with and without the open-stubs, (b) the current densities of the structure without loaded open-stubs, and (c) the current densities of the structure with loaded open-stubs.

spurious harmonics is similar to the lowpass filter as proposed in [18]. However, in this paper we built up the loaded open-stubs at the port feed, resulting in size reduction and wide-range spurious harmonics suppression.

Figure 14 shows a photograph of the fabricated filter. In this case, the size of the filter is 37.6 mm × 21 mm, or only approximately $1.09\lambda_g$ by $0.61\lambda_g$, where λ_g is the guide wavelength on the substrate at the center frequency.

The proposed filter has been then measured using a network analyzer. Fig. 15(a) shows a comparison of measured and simulated frequency responses. It can be found that the measured result is in good agreement with the simulation expectation. The measured passband of frequency response has been found to be 4.2–8.6 GHz

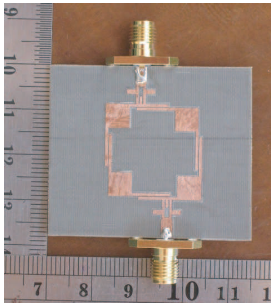
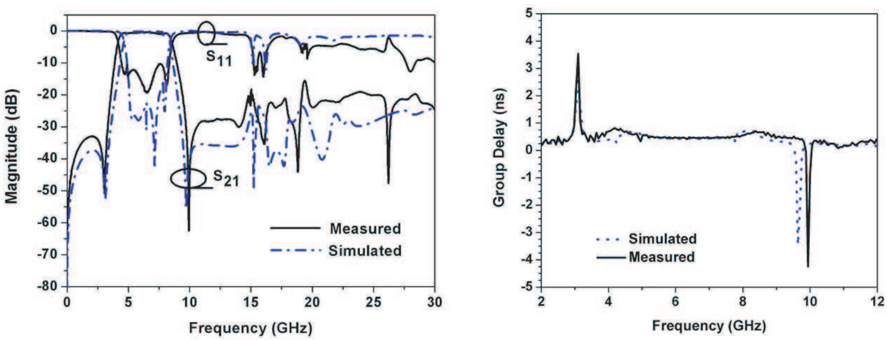


Figure 14. Photograph of the proposed filter.



(a) (b)

Figure 15. Comparisons of the measured and simulated responses (a) S_{11} and S_{21} and (b) group delay.

(FBW = 67.7%). The insertion loss is lesser than 0.25 dB and the return loss is better than 12 dB. Moreover, the sharp passband response with transmission zeros at 3.1 GHz and 9.3 GHz has been found. This filter structure obtains a wider superior response at the upper stopband. The filter has a rejected level lower than 20 dB from 9.3 to 30 GHz ($4.6f_0$). The group delay of the filter has been measured and compared with the simulation, which slightly variation between 0.3 to 0.4 ns in the passband is obtained as shown in Fig. 15(b).

4. DISCUSSION AND CONCLUSION

The wideband bandpass filters using the parallel-coupled SIRs with the wide spurious suppression are illustrated in Fig. 16(a). The simulated transmission performances are shown in Fig. 16(b), where

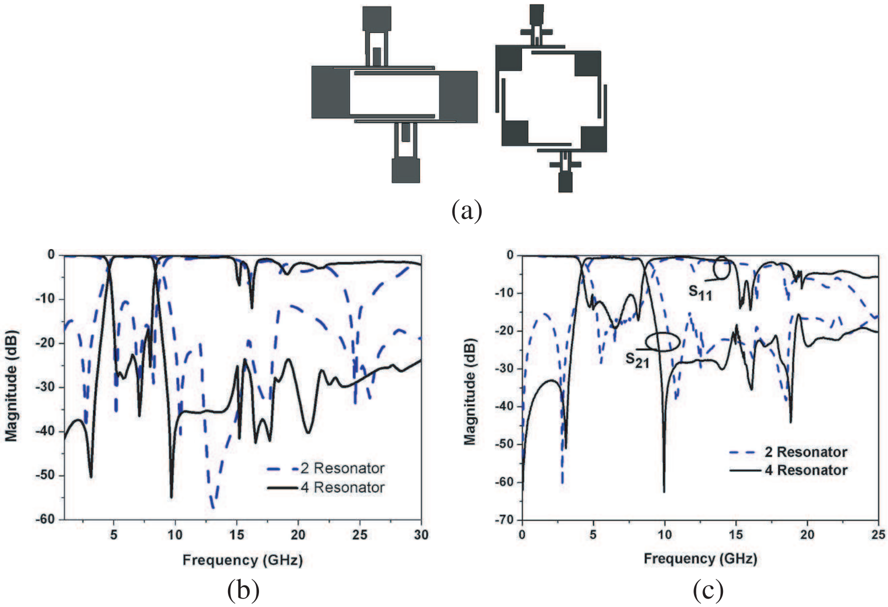


Figure 16. (a) Layout of the proposed filters and (b) comparison of simulated frequency responses and (c) comparison of experimental results.

the passband attenuation is about 0.22 dB. The spurious suppression of the two-resonator is greater than 20 dB from 10.42 to 18.15 GHz. The performances can be improved by using the four-resonator parallel-coupled bandpass filter with the embedded slot feeds and loaded open-stubs. The sharper passband response and greater spurious response suppression have been obtained. The spurious suppression exceeds 35 dB from 9.71 to 15.1 GHz and 25 dB from 15.1 to 30 GHz. Moreover, the transmission zeros of the passband response of the four-resonator filter are deeper than the two-resonator filter. Therefore, the improved shape factor has been obtained for the second filter.

These new wideband bandpass filters have been proposed for improving the spurious suppression. The filter performances have been extensively investigated by simulation and measurement as shown in Fig. 16(c). The proposed two-resonator filter has a wide fractional bandwidth around 73.8% and wide spurious suppression caused by $\lambda/2$ slots. This filter has not only a wider upper stopband, which the insertion loss is higher than 16 dB, but also a compact size. For the four-resonator filter, the measured results are in good agreement with the simulation expectation. The measured passband of frequency response has been found to be 4.2–8.6 GHz (FBW = 67.7 %). The insertion loss in the passband is lesser than 0.25 dB and the return loss is better than 15 dB. Moreover, the transmission zeros are 3.1 GHz at the lower passband skirt and 9.3 GHz at the higher passband skirt. The shape factors of the two- and four- resonator filters are 1.7 and 1.5, respectively. The four-resonator filter obtains the wide-range response of the upper stopband and rejected level lower than 20 dB from 9.3 to 30 GHz ($4.6 f_0$). As the results, the proposed method is very useful for wideband bandpass filters suitable for wireless communication systems.

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