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COMPACT BROADBAND DUAL-BAND BANDPASS FILTERS USING SLOTTED GROUND STRUCTURES

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Abstract—Dual-band bandpass filters featuring compact size and flexible frequency choice are demonstrated using resonators based on slotted ground structures. Two resonators based on slotted ground structures form the basis of the filter design. The resonators allow the back-to-back and face-to-face embedding configuration, hence, greatly reduces the physical size of the filters. By changing the sizes of the two resonators independently, the lower and upper resonance frequencies can be adjusted to the desired values. A dual-band broadband bandpass filter was implemented with good compactness and low insertion loss. A good agreement is obtained between the simulation and measurement results.

1. INTRODUCTION

With the advent of wireless communications, the design of many passive circuits, such as the bandpass filters, are facing new design challenges including compact size, wide bandwidth and multi-band operations. For example, high data-rate wireless communication systems, such as worldwide interoperability for microwave access (WiMAX) and wireless local area network (WLAN), require wide bandwidth up to several hundred of megahertz and flexibility of operating in multiple frequency bands. Planar bandpass filters fabricated on printed circuit board (PCB) are attractive for filter application because their low fabrication cost suits commercial application well [1–4]. The multi-band microwave components, when realized, can lead to both the size and cost reduction in the circuits used for multi-band wireless communication systems [5–10].

Recently, several approaches have been developed for achieving dual-band operation in bandpass filters. A straightforward method is to design a dual-band bandpass filter consisting of two bandpass filters that were independently designed for each band [11]. Weng et al. pointed out that this approach needs extra impedance matching networks for diplexer-like structure and requires a larger circuit size [12]. Another method of designing dual-band bandpass filter is to use a cascade connection of open- or short-circuited stub structures to achieve a dual-band performance [13, 14]. Once again, this approach requires increased circuit complexity and physical size. Stepped impedance resonators (SIR) are suitable for the filter design because the higher order resonant modes could be shifted or suppressed, and the spurious frequency response can be used to create the second passband for dual-passband response [15, 16]. However, the second passband is limited by the practical impedance ratio of the SIR resonator. In most of the reported works, such as [11, 13, 15], poor insertion loss in the two passbands is at presence due to the weak coupling, or the discontinuities appearing in the stepped impedance resonator with very high impedance ratio.

During the last decade, patterned ground structures, which have also been referred as 'defected' or 'slotted' ground structures have been investigated. Many useful characteristics have been reported, including stopband and slow wave effects. These slotted ground structures have been applied for various applications including spurious-suppression of lowpass filters [17], harmonic-suppressions for amplifiers and antennas [18, 19], band-accepted configuration of bandpass filters [20–23]. Recently, we have shown that the slotted ground structure can be made more compact by lengthening the coupling gap, which results in increased coupling capacitance. The compact slotted ground structure was applied to a tunable bandstop resonator. In general, the slotted ground structures exhibit advantages including efficient and flexible usage of the ground plane, compactness, and wide-band operation. The broadband feature is especially attractive for applications in high data-rate communication systems.

In this paper, broadband bandpass filters with dual-band operation are designed and demonstrated using slotted ground structure. These filters feature compact size, wide bandwidth, low insertion loss, and design flexibility in the passbands' frequencies. In addition to the compact slotted ground structure reported previously [24], another compact slotted ground structure is designed for the purpose of allowing the two structures being embedded with each other. A back-to-back and a face-to-face second-order bandpass filter based on two new compact slotted ground structures are presented. It is shown that the back-to-back structure can be embedded in the face-to-face structure completely, allowing a compact filter structure featuring two resonators operating at two different resonant frequencies. Therefore, a dual-band bandpass filter can be formed. The lower and upper passband can be controlled by the two single band filters, respectively. The proposed dual-band filter with passband at 2.4 and 5.2 GHz is designed and fabricated on Rogers RT/Duroid 3006 printed circuit board (PCB). A good agreement is obtained between the simulation and measurement results. Especially, the insertion loss is less than -1 dB within both of the passbands.

In Section 2, the back-to-back and face-to-face slotted ground resonators are illustrated featuring compact size. Compared to the conventional dumbbell-shaped resonator, the resonant frequencies of the two new resonators (*Type I* and *Type II*) are reduced. A back-to-back configuration of *Type I* resonator and a face-to-face configuration of *Type II* resonator provide second-order bandpass filters that are designed and simulated by full-wave simulator, *IE3D*, in Section 3. The filters' equivalent circuits are also proposed, respectively. In Section 4, a dual-band filter featuring compact size, low loss, and flexible passbands is developed by overlaying the back-to-back and face-to-face filters. Section 5 provides the concluding remarks.

2. DESIGN AND CHARACTERISTICS OF TWO NEW SLOTTED GROUND RESONATORS

In the past years, various slotted ground resonators were proposed in [17, 25, 26], such as dumbbell-, spiral-, H-shaped resonance cell. The typical structure is dumbbell-shaped resonator shown in Fig. 1(a). The self resonance frequency (f_0) of the cell depends on the physical dimensions. For example, f_0 can be reduced by using smaller gap c, larger a and b, or larger distance d between the two large openings of the dumbbell pattern. Since c is generally limited by printed circuit fabrication techniques, increasing the size of the dumbbell-shaped cell is the practical approach of reducing f_0. Thus, the lower is f_0, the larger are the physical dimensions. The proposed resonant cells, *Type I* and *II* (*Type II* has been discussed in details in [24]) as shown in Figs. 1(b) and (c), are based on moving the coupling gaps to the edges of the slotted holes and lengthening the coupling slots. To compare the compactness of the three structures in Fig. 1, the transmission coefficient (S_{21}) of microstrip lines on top of these structures is simulated. The simulations are performed using a full-wave simulator, i.e., *IE3D*. The substrate used in the simulation has the same parameters as the Rogers RT/Duroid 3006, with a board thickness of 1.27 mm, a dielectric constant of $\varepsilon_r = 6.15$ and a loss tangent of 0.0025. In the simulations, the distances, d, g, k, are kept at a fixed value and are the same as the width of the 50 Ohm microstrip feed lines.

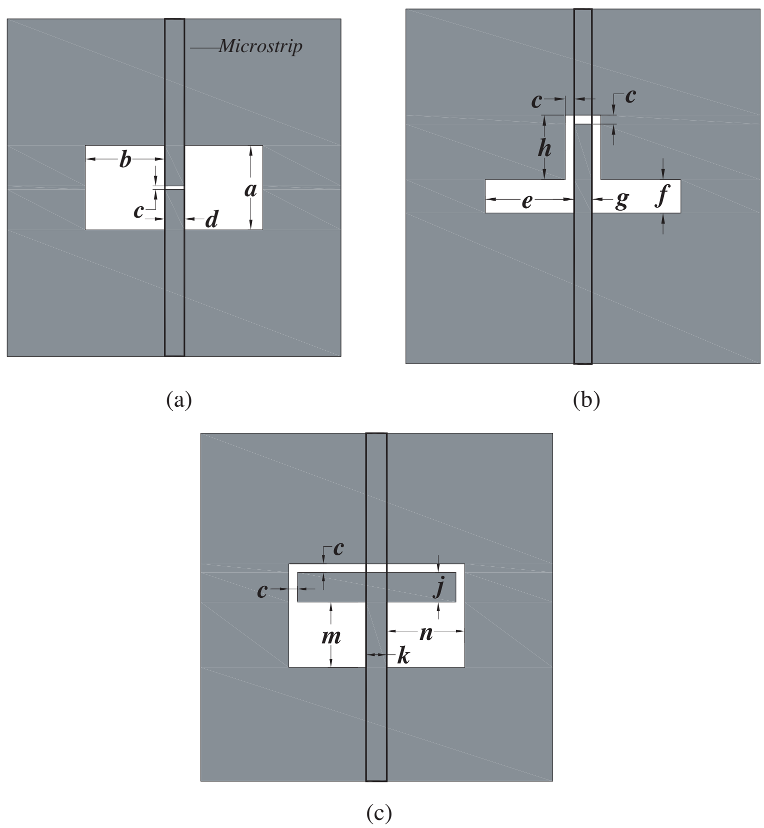


Figure 1. Schematic layout of various slotted ground cells: (a) dumbbell-shaped cell in [17], (b) our proposed cell, *Type I*, (c) our proposed cell, *Type II*. The microstrip lines are outlined by the dark lines.

Figure 2 shows the results of S_{21} when the rectangular occupying areas of the three resonators are all the same. The details of the physical sizes are listed in Table 1. The resonant frequency (f_0) of the two new proposed cells, *Type I* and *II*, is 7.018 and 5.128 GHz, respectively. Compared to the conventional dumbbell cell that shows a resonant frequency of 8.151 GHz, the two proposed cells show better compactness. This compactness of the two proposed cells can be understood based on the parameters extracted from the equivalent circuit model (Fig. 3) proposed by Ahn et al. [17]. Table 1 compares the extracted equivalent circuit parameters of two proposed cells and the conventional dumbbell-shaped cell. It can be observed that the capacitance of the proposed cells is about three times of that of the conventional dumbbell-shaped cell. Thus, we can conclude that the extended gap length results in much increased capacitance. The reduced effective inductance of the two proposed cells is a result of the shorter metal traces needed for the compact structures.

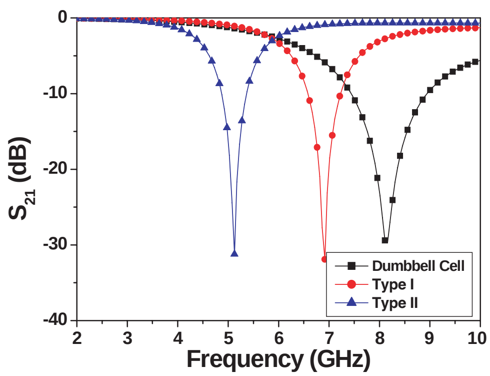


Figure 2. Simulated S_{21} of the three structures (as drawn in Fig. 1) with the same rectangular occupying area.

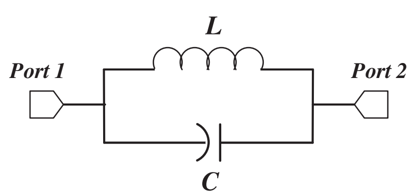


Figure 3. An equivalent circuit model for slotted ground structure.

Table 1. Physical size and extracted equivalent-circuit parameters for the three mentioned structures.

	Dumbbell Cell	*Type I*	*Type II*
Size (mm)	$a = 3$, $b = 2$, $c = 0.2$, $d = 2$.	$c = 0.2$, $e = 2$, $f = 1$, $g = 2$, $h = 2$.	$c = 0.2$, $j = 0.4$, $k = 2$, $m = 2.4$, $n = 2$.
Inductance (nH)	1.083	0.561	0.929
Capacitance (pF)	0.352	0.916	1.037
Cutoff Frequency (GHz)	6.198	6.203	4.418
Attenuation Pole Location (GHz)	8.151	7.018	5.128

3. TWO SECOND-ORDER BANDPASS FILTERS

In the previous section, two slotted ground resonators, *Type I* and *II* in Fig. 1, were proposed, which show good compactness compared to the conventional dumbbell-shaped resonator. Hereafter, they would be applied to design bandpass filters.

3.1. Back-to-Back Bandpass Filter

A back-to-back bandpass filter is designed with a schematic layout shown in Fig. 4. This filter consists of two identical slotted ground resonators (Fig. 4(a)), *Type I*, and the feed line coupling is achieved with a simple gap capacitor (Fig. 4(b)). With $e = 2.6\,\text{mm}$, $f = 0.8\,\text{mm}$, $g = 1.3\,\text{mm}$, $h = 2.7\,\text{mm}$, $p = 1.6\,\text{mm}$, $g_1 = 0.4\,\text{mm}$, $g_2 = 0.8\,\text{mm}$, $l = 2.8\,\text{mm}$, $w = 2\,\text{mm}$, the simulated results of S-parameters by *Zeland IE3D* are plotted in Fig. 5. The insertion loss is 1.2 dB at 5.6 GHz. And two transmission zeros appear in the upper stopband. In this back-to-back filter, the slotted resonators provide a transmission zero at their self-resonance frequency of 6.33 GHz. The gap capacitor feed line not only improves the propagation characteristics of the passband by the improved electrical coupling, but also provides another transmission zero at 6.98 GHz. The reason is that the feed line and the slotted ground structure form a series inductance (L) and capacitance (C) resonator. The equivalent circuit model of this filter is shown in

Fig. 6. C_0 is the interdigital capacitance of the feed line. Parallel L_1 and C_1 (corresponding to the slotted ground resonators), series L_2 and C_2 (corresponding to the interdigital capacitor feed line and the slotted ground) provide the two transmission zeros. The last simulated result by *Advanced Design System* (*ADS*), in Fig. 5, shows there is a good agreement between the full-wave and circuit simulation.

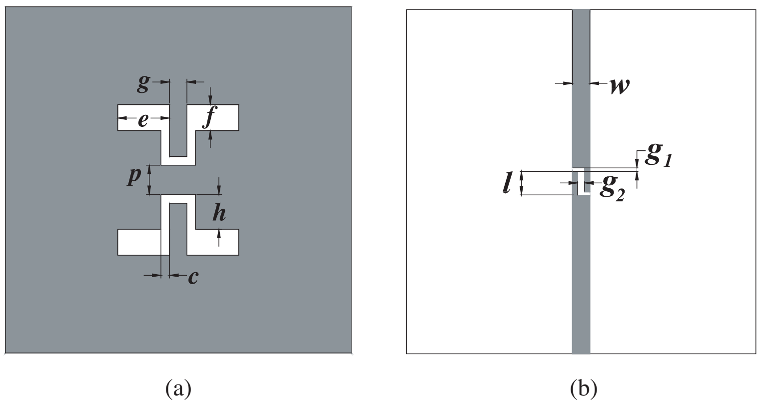


Figure 4. Layout of back-to-back filter: (a) view of the ground plane, (b) view of the signal plane.

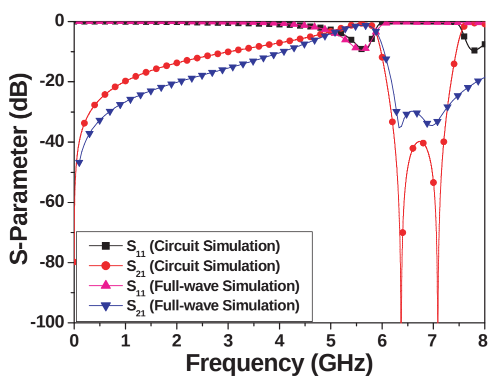


Figure 5. Simulated results of the back-to-back bandpass filter by *IE3D* and *ADS*.

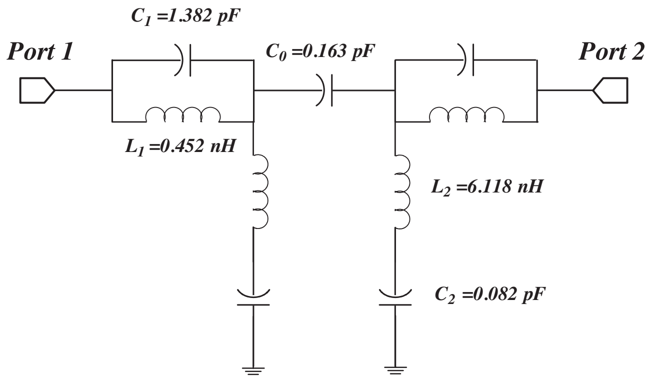


Figure 6. An equivalent circuit model for the back-to-back bandpass filter.

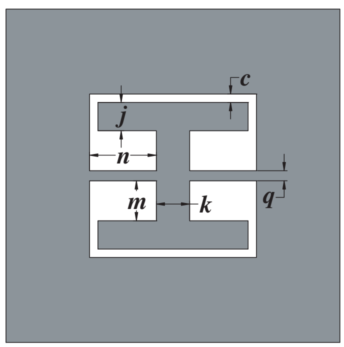


Figure 7. The ground plane of face-to-face filter.

3.2. Face-to-Face Bandpass Filter

In previous subsection a back-to-back bandpass filter with the cell, *Type I*, was introduced, which upper stopband has two transmission zeros. Here, a face-to-face bandpass filter would be introduced using the cell, *Type II*. Its ground plane is shown in Fig. 7, and the feed line is the same as that of the mentioned back-to-back filter. In this filter, the signal trace is coupled from feed line to ground plane by the first slotted ground resonator. Then, it is transmitted from the first resonator to the second resonator. Finally, the signal is coupled back from ground to the feed line by the second resonator. Fig. 8 gives the simulated result by *IE3D* when $c = 0.2\,\mathrm{mm}$, $j = 1.9\,\mathrm{mm}$, $k = 2.4\,\mathrm{mm}$, $m = 2.9\,\mathrm{mm}$, $n = 3\,\mathrm{mm}$, $q = 0.2\,\mathrm{mm}$, $g_1 = 0.4\,\mathrm{mm}$, $g_2 = 0.8\,\mathrm{mm}$, $l = 2.8\,\mathrm{mm}$, $w = 2\,\mathrm{mm}$. The insertion loss is about $0.2\,\mathrm{dB}$ in the passband. And there are two transmission zeros at 1.6 and 4.1 GHz near the passband, respectively. Similar to the work reported in [23], the upper transmission zero is due to the coupling between the feed line and the second resonator, and the lower transmission zero is due to the cross coupling between the input and output feed lines. In Fig. 9, its equivalent circuit model is proposed. C_0 is the capacitance value of the interdigital capacitor feed line. Parallel L_1 and C_1 represent the slotted ground resonators. L_0 represents the inductance of the metal line between the two resonators. The circuit simulation results, shown in Fig. 8, are obtained by *ADS*. Good agreement is obtained between full-wave and circuit simulation. Compared to the second-order filter in [22], the total circuit size is reduced greatly and it does not need the stubs to provide the transmission zero.

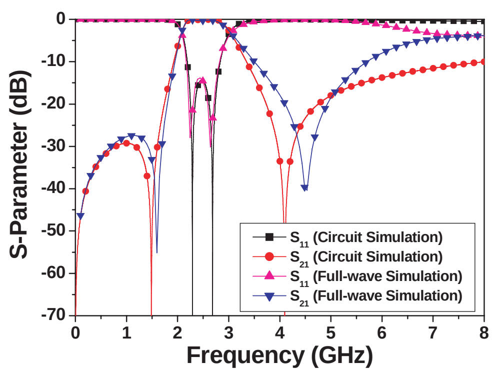


Figure 8. Simulated results of the face-to-face bandpass filter by *IE3D* and *ADS*.

4. FLEXIBLE BROADBAND DUAL-BAND BANDPASS FILTER

Single band bandpass filters with slotted ground structure were proposed in [20–23]. The slotted ground resonators can be used to create the transmission zeros, such as [21, 22], or to create the passband, such as [23]. The slotted ground resonators can be also used to suppress the harmonics of the stopband, such as [20]. However, to our best knowledge, there is a lack of study in designing dual-band bandpass filters with the slotted ground structures directly. For applications in WLAN or WiMAX systems, a new dual-band bandpass filter, consisted of two bandpass filters proposed in Section 3, would be introduced here. Unlike the previous approaches that need extra

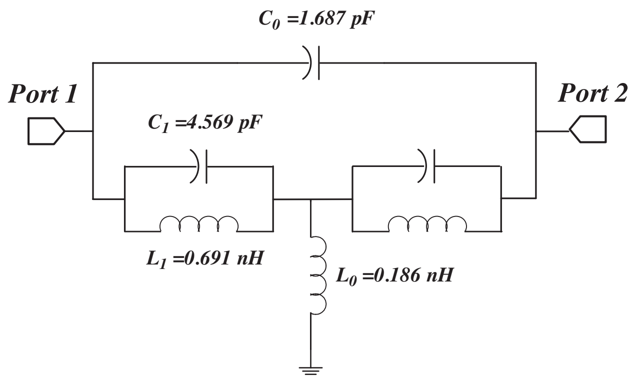


Figure 9. An equivalent circuit model for the face-to-face bandpass filter.

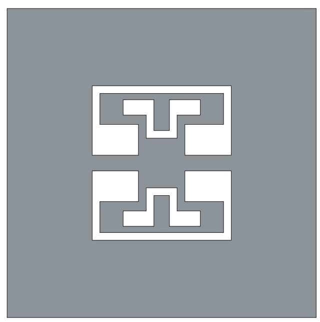
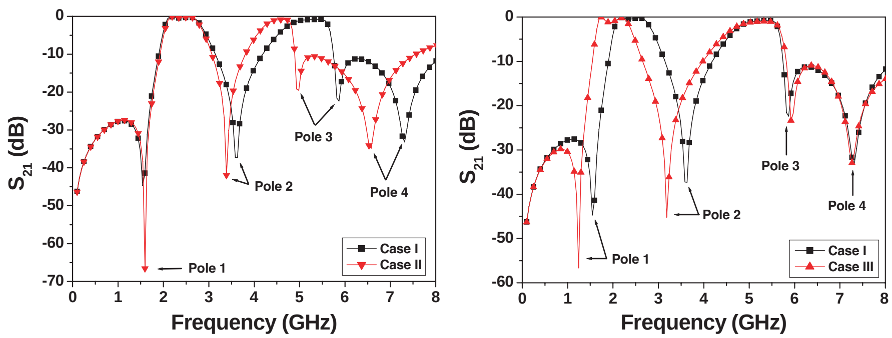


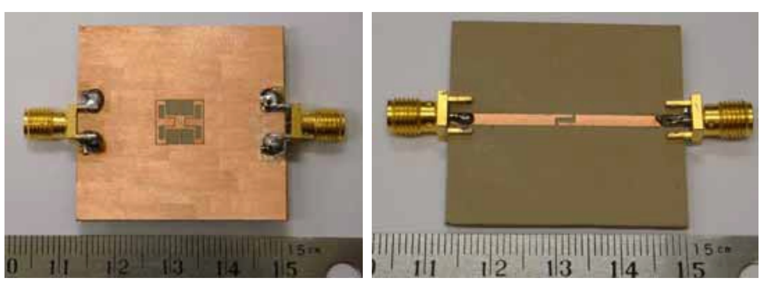
Figure 10. Ground plane of the dual-band bandpass filter.

impedance matching networks and result in a large circuit size, such as [12, 15], the filter proposed here does not need the impedance matching line in the input and output ports, and the dual-band operation does not need to pay the size penalty. Two single band filters corresponding to two different passbands (centered at 2.4 and 5.2 GHz) are embedded with each other. The slotted ground plane is shown in Fig. 10, and the feed line is the same as that shown in Fig. 4(b). With the same physical dimensions as those of the back-to-back and face-to-face filter in *Sections 3.1* and *3.2*, the simulated S_{21} of the new bandpass filter is shown in Fig. 11, corresponding to *Case I*. Two passbands with 0.84 and 0.97 GHz bandwidth centered at 2.4 and 5.2 GHz are obtained, respectively. The lower and upper passband in the proposed structures can be controlled independently, as shown in Figs. 11(a) and (b) comparing the results of three different cases. Fig. 11(a) shows a shifted upper passband by increasing the size of the cell in the back-to-back bandpass filter, corresponding to *Case II*. Here, e and f are increased from 2.7 to 3.2 mm, and 0.8 to 1.1 mm, respectively. It can be found that there is a shift in the second passband while the first passband remains the same. *Pole 1*, corresponding to the first passband, is constant in *Case I* and *II*. *Pole 2*, *3*, and *4* are all moving together with the second passband. Fig. 11(b) shows the changes of lower passband by increasing m and n from 2.9 to 3.4 mm, and 3.0 to 4.0 mm, corresponding to *Case III*. *Pole 1* and *2* are moving with the first passband while *Pole 3* and *4* remain little changed as the upper passband. It is concluded that the proposed dual-band filter has good design flexibility in obtaining desired passbands.



(a) (b)

Figure 11. Simulated results of three cases: (a) shifted upper passband, (b) shifted lower passband.



(a) (b)

Figure 12. Photograph of the fabricated filter: (a) view of the ground plane, (b) view of the signal plane.

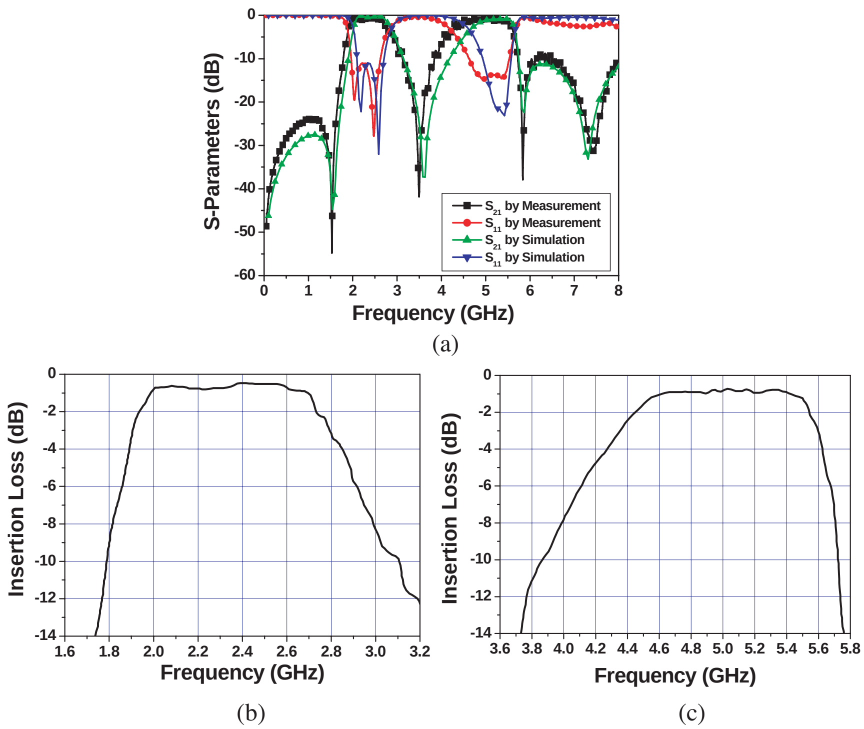


Figure 13. (a) Simulated and measured results of the dual-band bandpass filter; The detailed insertion measured in the two passbands are plotted in (b) and (c).

The filter as described as *Case I* was fabricated on Rogers RT/Duroid 3006 PCB. The occupying area of the slotted ground resonators is only 85.68 mm^2. Compared to a recent work that needs an impedance matching network for the feed line [12] and takes about 250 mm^2, the size of the new filter is greatly reduced. The measurement results are shown in Fig. 13(a). Good agreement is achieved between the simulated and measured results. The average insertion loss of the lower wide passband is about 0.75 dB as shown in Fig. 13(b), and that of the upper wide passband is about 1.0 dB as shown in Fig. 13(c). The insertion losses of the new filter are 1 dB lower than those designed by the stepped impedance method in [11, 13, 15]. The 3 dB bandwidth of the lower passband is from 1.90 to 2.78 GHz, and that of the upper passband is from 4.27 to 5.60 GHz. These results show broadband operations that are required in high data-rate wireless communication systems. Fig. 14 shows the group delay in the two passbands.

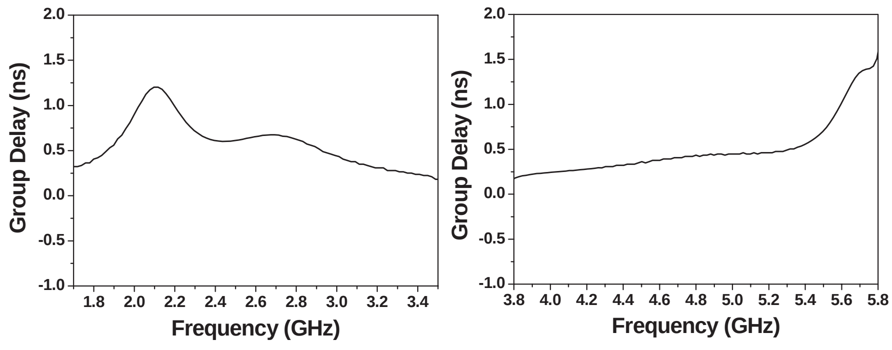


Figure 14. Group delay in the two passbands: (a) the lower passband, (b) the upper passband.

The packing influence and the effect of a closely placed ground plane were investigated by placing a grounded metal wall closely to the slotted ground structure, at a distance of 7 mm and 2 mm ($< 0.04\lambda$ of the entire upper band), respectively. The effect of the metal wall was negligible within the two passbands, as illustrated in Fig. 15.

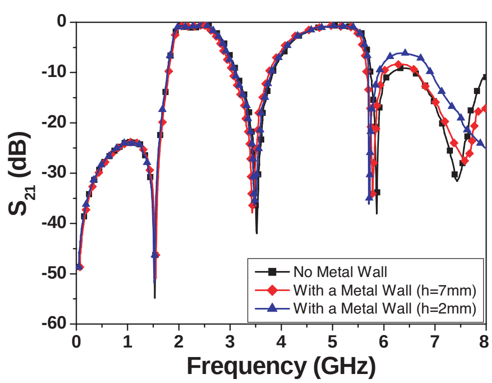


Figure 15. The effect of a closely placed metal wall on the dual-band bandpass filter using slotted ground structures.

5. CONCLUSION

In this paper, a new approach of designing broadband dual-band bandpass filters using slotted ground structures was demonstrated.

Two resonators realized by slotted ground structures can be used to construct back-to-back and face-to-face second-order bandpass filter. By embedding the two bandpass filters with each other, dual-band bandpass filters are demonstrated. These dual-band bandpass filters feature compact size, wide bandwidth and low insertion-loss. In addition, since the dual-band filters consist of two single-band bandpass filters, the lower and upper passband could be designed independently. Thus robust choice of frequency ratio of the two passbands can be achieved, unlike the approach based on stepped impedance resonator. The new dual-band filters show good in-band and out-band characteristics, providing promising applications in the multi-band wireless systems.

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