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# A wideband stepped-impedance rectangular-ring resonator bandpass filter with multiple notched bands

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# A wideband stepped-impedance rectangular-ring resonator bandpass filter with multiple notched bands

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A configuration of wideband bandpass filter (BPF) with multiple notched bands is presented. Proposed BPF is based on stepped-impedance resonator. By utilising dual stepped-impedance resonators in folded topology a rectangular-ring resonator is formed. Two notched bands in the passband are achieved without using asymmetrical coupled lines. In other words, the filter configuration is capable of producing notched bands. It should be noted that additional information on filter performance and design is presented. Measurement results are presented to approve propounded filter characteristics. The measured passband of the second proposed filter is from 3.68 to 10.2 GHz with insertion loss of –1.76 dB in the first passband at the centre frequency of 4.45 GHz. The measured notched band frequencies are about 5.45 and 7.95 GHz with rejection of –21.77 and –20.82 dB, respectively. The return loss in the passband is better than –11.4 dB.

**Keywords:** ring resonator; stepped-impedance; wideband; bandpass filter; notched band



## 1. Introduction

Bandpass filters (BPFs) are essential building blocks for communication systems. Design of wideband BPF and overcoming its challenges is one of the engrossing topics. Among various reported configurations, ring resonator is very popular. This type of resonator was first introduced by Wolff (1972). Later, many researches and studies have been reported to design BPF based on this type of resonator (Gorur, 2004; Hsieh & Chang, 2002, 2003; Kuo & Tsai, 2006; Matsuo, Yabuki & Makimoto, 2001; Srisathit, Worapishet & Surakampontorn, 2010; Sun & Zhu, 2007; Zhu & Wu, 1999). This type of filter is well-known because of its dual-mode characteristic. By utilising orthogonal feed lines and perturbations, two degenerate modes of a dual-mode resonator can be excited and coupled to each other to realise a BPF with a narrow bandwidth (Kundu & Awai, 2001; Matsuo et al., 2001). Moreover, by using some techniques which can separate these two orthogonal modes, achievement of a wideband BPF is not very difficult. For example, control of these two degenerate modes with different characteristic impedances by utilising stepped-impedance ring resonator was reported in Matsuo et al. (2001). Description of coupling between degenerate modes of a dual-mode ring resonator is reported in Gorur (2004). For extension of upper stopband, periodic stepped-impedance ring resonator was propounded (Kuo & Tsai, 2006). It's noteworthy that many ring resonators with different coupling approaches were reported (Hsieh & Chang, 2002, 2003; Sun & Zhu, 2007; Zhu

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& Wu, 1999). However, in comparison with direct connecting configuration, the capacitive gap or coupled line technique engender some interesting features, embracing dc-rejection and highly attenuation of stopband (Sun & Zhu, 2007). By stretching the paired stubs close to one-eighth of the wavelength, a triple-resonance ring resonator BPF has been proposed (Sun & Zhu, 2007). The proposed filter exhibits some attractive features such as low insertion loss and good out-of-band performance. A triple-mode ring resonator by utilising open-ended coupled lines and open stub was proposed in design of BPF with high selectivity characteristics (Srisathit et al., 2010).

On the other hand, by rapid development of multiband and wideband wireless communication systems, it is not far from imagination that these systems might interfere with each other. Obviously, many wideband and ultra-wideband (UWB) BPFs with capability of rejecting specific frequency bands have been reported (Hao, Hong, Parry, & Hand, 2009; Li, Li, Liang, & Wu, 2010; Luo, Ma, Ma, & Yeo, 2010, 2011; Sekar & Entesari, 2011; Shaman & Hong, 2007; Shi, Choi, Chen, Tam, & Xue, 2012; Wei, Wu, Shi, & Chen, 2011; Wu, Shim, & Rais-Zadeh, 2012). A compact UWB BPF with a notched band was introduced, which employed a split-ring resonator defected ground structure (DGS) (Li et al. 2010). Based on a simplified composite right/left-handed (SCRLH) resonator, a UWB BPF with dual sharply rejected notch-band was proposed (Wei et al., 2011). Compact UWB BPF with ultra-narrow dual and quad notched bands by using the broadside-coupled microstrip/coplanar waveguide (CPW) structure were reported in Luo et al., (2010, 2011). A multiple-mode UWB operation was obtained through the CPW detached-mode resonator (DMR) and broadside-coupled microstrip/CPW transition. By introducing embedded quarter-wavelength (λ/4) CPW resonators and λ/4 meander slot line inserted in the DMR, multiple notched bands were achieved. One of the main drawbacks of the reported filter is that in the design of quad notched bands, a fabrication tolerance of 0.1 mm is required. On the other hand, simulated filter response indicates that the achievement of return loss, i.e., $S_{11}$, below –10 dB is difficult. It is worth mentioning that this BPF is very compact, i.e., 0.345 $\lambda_g$ × 0.462 $\lambda_g$, where $\lambda_g$ is the microstrip guided wavelength at 6.52 GHz. Another wideband BPF using ring-resonator with dual stepped-impedance stubs was propounded (Kim & Chang, 2010a). This filter exhibits interesting features and characteristics including precipitous slopes and high attenuation at the stopbands. Later, an attempt to design a BPF with switchable bandwidth based on this structure was reported (Kim & Chang, 2010b). In Kim and Chang (2011), an UWB BPF with a notched band by utilising asymmetric structure in interdigital coupled feed lines was proposed. Bandwidth of this UWB BPF with the aid of two-stepped-impedance stubs can be controlled. Recently, a microstrip UWB differential filter with a notched band based on the transversal signal interference concept is proposed (Shi et al., 2012). In this filter, the notched band is implemented by coupling with quarter wavelength shorted-lines at input and output ports. Slot line DGS is used for improving the common mode rejection.

Recently, a wideband ring resonator BPF with two notched bands without utilising asymmetric coupled feed lines has been proposed (Nakhlestani, Movahhedi, & Hakimi, 2012). The proposed filter by implementation of stepped-impedance resonator and multiple path in its structure is capable of rejecting unwanted frequencies. As mentioned above, ring resonator filters exhibit wide bandwidth with sharp cut-off frequencies. Therefore, in this study a ring resonator is used to provide a wide bandwidth with capability of rejecting interference signals of other communication channels. To the authors' best knowledge, ring resonator BPFs with notched bands have been rarely reported and this work by propounding a new configuration for ring resonators presents a ring resonator BPF with multiple notched bands. Another advantage of the proposed filter in comparison with configurations with asymmetric coupled lines is that it can provide two notched bands. In this paper, the proposed configuration in Nakhlestani et al. (2012) is fully investigated and structure physical parameters are studied on the filter performance. Analysis of microwave circuits and structures is sometimes difficult, such as extraction of the resonant frequencies of the proposed filter, analytically. Therefore, various figures about design of the proposed filter are illustrated. In other words, presented figures in this paper can give insight how to design a filter by trial and error. Provided figures discuss how bandwidth, selectivity and notched band frequency vary under given parameters and conditions and how to tune them to achieve best possible response.

This paper is organised as follows. Section 2 discusses the filter analysis. In Section 3, the measurement results are provided while conclusions are presented in Section 4.



## 2. Analysis of the proposed wideband BPF

In this section, analysis of the proposed filter is presented. To investigate filter performance, design parameters are extracted and studied in this section in terms of transmission line theory. First, the even and odd mode analysis results are discussed. Subsequently, full-wave simulation results with the aid of Agilent Advanced Design System (ADS) software are presented.

### 2.1. *Extraction of resonant frequencies*

Since, the filter is symmetrical, even and odd modes analysis approach can be applied to analyse it (Pozar, 1998). Filter structure and equivalent models of even and odd modes, for filter analysis, are shown in Figure 1(b) and (c). For odd mode excitation, the middle points of the filter structure, which form the symmetrical plane, are short circuited but for even mode excitation, these middle points are open circuited. Resonance conditions can be used to extract resonant frequencies by assuming $Y_{in} = 0$ or $Z_{in} = 0$ from even and odd mode equivalent circuits, respectively (Pozar, 1998). Analysis of a four-section stepped-impedance structure based on deriving its input impedance equation is very difficult and does not provide intuition about filter performance (Liu, Yang, Yang, Da, & Gong, 2009). After analysis of the filter, results can be explained with the help of Figures 2–4. As it can be seen from Figure 2, a triple-mode filter, based on $F_1$, $F_2$, and $F_3$, is formed. $F_n$ is the notched band resonant frequency and distinguishes passbands. By choice of appropriate parameters, the first passband can be formed before $F_n$ while the second one can be placed

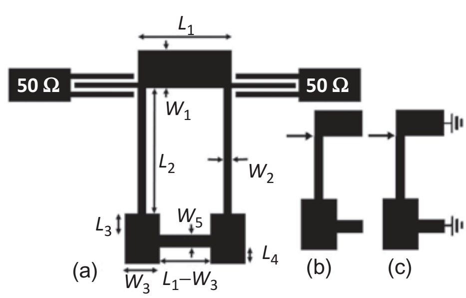


Figure 1. Proposed filter structure with coupled feed lines.

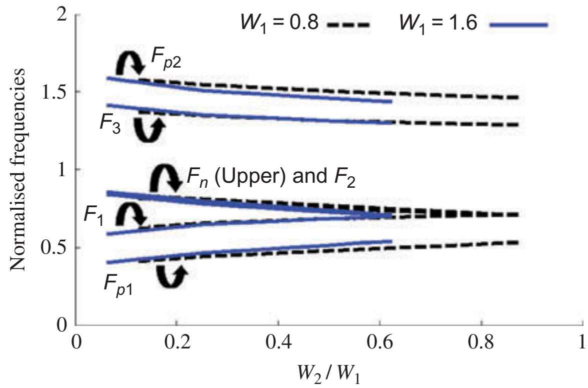


Figure 2. Resonant frequencies versus $\frac{W_2}{W_1}$ while other parameters are: $L_1 = 4.8$, $L_2 = 6.6$, $L_3 = 1.6$, $L_4 = 1$, $W_3 = 1.6$, and $W_5 = 0.2$, unit: mm.

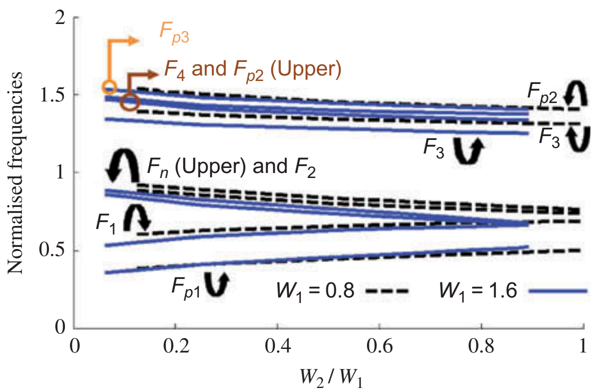


Figure 3. Resonant frequencies versus $\frac{W_2}{W_1}$ while other parameters are: $L_1 = 4.8$, $L_2 = 6.6$, $L_3 = 1.6$, $L_4 = 1$, $W_3 = 1.6$, and $W_5 = 0.8$, unit: mm.

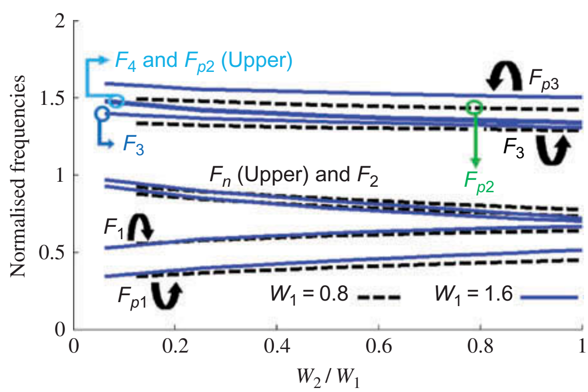


Figure 4. Resonant frequencies versus $\frac{W_2}{W_1}$ while other parameters are: $L_1 = 4.8$, $L_2 = 6.6$, $L_3 = 1.6$, $L_4 = 1$, $W_3 = 1.6$, and $W_5 = 1.6$, unit: mm.

after it. $F_{p1}$ and $F_{p2}$ control the filter selectivity and closeness of $F_{p1}$ to $F_1$ ensures a sharp slope at the lower stopband. Closeness of $F_{p2}$ to the nearest resonant frequency of the passband, i.e., $F_3$, provides a sharp slope at the upper stopband. In this analysis, it has been assumed that $W_3/W_5 = 1.6/0.2$ to obtain this figure. As shown in Figure 2, by increment of $W_1$, the range of this behaviour would be limited. For a wider $W_1$, a narrower $W_2$ is required. Therefore, this situation may demand higher cost because a more accurate fabrication tolerance is required. It can be seen from Figure 2 that by chosen values of design parameters, as shown in caption of the figure, $F_2$ and $F_n$ would be very close together.

Now, $W_3$ / $W_5$ is changed to 1.6/0.8 and the variation of the frequency response of the resonator is investigated. The result of this modification is illustrated in Figure 3. The number of resonant frequencies of the filter is increased which can obviously improve the filter performance that will be described as follows. $F_4$ and $F_{p3}$ are additional resonant frequencies. Hence, the second passband, which is after the notched band, has an additional resonant frequency, i.e., $F_4$, which is very close to $F_{p2}$ and can lead to a sharp filter at the upper band. In addition, $F_{p3}$ can increase the attenuation of the upper stopband. By increment of $W_2$ / $W_1$, then $F_{p2}$ and $F_{p3}$ become very close together while $F_4$ and $F_{p2}$ split away. Closeness of $F_{p2}$ and $F_{p3}$ indicates that filter would provide a highly attenuative upper stopband. For $W_1 = 0.8$ mm, no additional resonant frequency is appeared as shown in Figure 3. Although no increase in resonant frequency is seen in Figure 4 in case of $W_1 = 0.8$, there are some interesting changes in frequency response for additional resonant frequencies in case of $W_1 = 1.6$. $F_{p3}$ and $F_{p2}$ are being far away from each other which shows a wider upper stopband compared to Figure 3. However, this wider stopband indicates that the filter cannot provide a sharp rejection at the upper stopband. The similar words about more separation of $F_n$ and $F_2$ is subsisted. Closeness of $F_3$ and $F_4$ under these conditions is more obvious by increasing $W_2$ / $W_1$ which is quite different as shown in Figure 3, where $F_3$ and $F_4$ are not strongly affected by variation of $W_2$ / $W_1$ and not so close together as can be seen here. By now, it can be concluded that $W_5$ can be affected on displacement of the notched band, as mentioned above. It should be noted that the change of the width of $W_5$ can change the filter performance and clearly limits the displacement of the notched band.

Now, variation of $\theta_1$ / $\theta_2$ on the filter response is investigated, where $\theta_1$ and $\theta_2$ are electrical lengths of $L_1$ and $L_2$, and results are depicted in Figure 5. The upper stopband is more selective than the lower stopband for larger values of $\theta_1$ / $\theta_2$ by choice of a wider

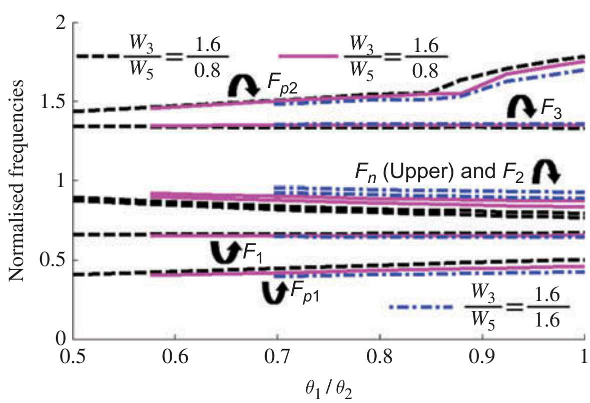


Figure 5. Resonant frequencies versus $\frac{\theta_1}{\theta_2}$ while other parameters are: $W_1 = 0.8$, $W_2 = 0.2$, $L_3 = 1.6$, and $L_4 = 1$, unit: mm.

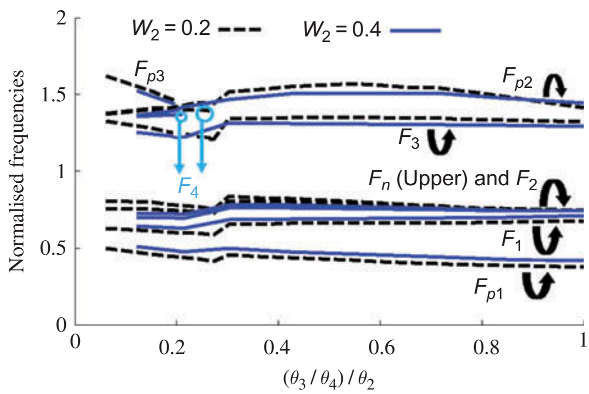


Figure 6. Resonant frequencies versus $(\theta_3 + \theta_4)/\theta_2$ while other parameters are: $L_1 = 4.8$, $L_2 = 6.6$, $W_1 = 0.8$, $W_3 = 1.6$, and $W_5 = 0.2$, unit: mm.

$W_5$. Wider $W_5$ results in wider bandwidth of the first passband and this is more clear for smaller values of $\theta_1$ / $\theta_2$. However, a wider $W_5$ requires a longer $L_1$. So, it reveals that a choice of a wide $W_5$ results in increment of the filter size. Final note which can be seen in Figure 5, is that for $\theta_1$ / $\theta_2$ near one, a wider upper stopband is expected at the cost of losing filter selectivity. By increasing $\theta_1$ / $\theta_2$, the bandwidth of the first passband is reduced and this reduction in case of $W_3/W_5 = 1.6/0.2$ is more evident.

Already, Figure 2 showed that for ratio of $W_3/W_5 = 1.6/0.2$ when $(L_3 + L_4)/L_2 = 0.39$, there are two resonant frequencies less than in the case of $W_3/W_5 = 1.6/0.8$ or $W_3/W_5 = 1.6/1.6$. However, Figure 6 exhibits that it is possible to have these additional resonant frequencies by choosing a small ratio of $(L_3 + L_4)/L_2$. But this appearance frontier of these additional frequencies is very limited, i.e., from 0.12 to 0.39 by setting $W_2 = 0.2$ mm. So, it can be concluded that the main factor of the appearance of these resonant frequencies is $W_5$. It should be noted that to obtain Figure 6, the stub with the width of $W_5$ was placed in the middle of the stub with the length of $L_3 + L_4$. The variation of $(L_3 + L_4)/L_2$ on the filter selectivity can be easily seen in Figure 6. For small ratios, the proposed filter provides a high selectivity at the lower stopband because of closeness of $F_{p1}$ and $F_1$. In case of upper stopband, by proper design parameters not only a sharp cut-off is expected but also a wider stopband, due to presence of $F_{p3}$, is possible. By choice of a ratio near one the chance of a sharp rejection at the upper stopband is possible due to closeness of $F_{p2}$ and $F_{p3}$. For middle ratios, the filter is less selective for both upper and lower stopbands compared to small ratios. However, for ratio near one, the upper stopband is more selective than the lower one at the cost of reduction of the bandwidth of the first passband. Figure 7 shows the behaviours of the resonant frequencies when $W_5$ is set to 0.8 mm. It is obvious that appearance frontier of $F_{p3}$ is almost unchanged for case of $W_2 = 0.2$ mm by comparing Figure 7 with Figure 6, but this appearance frontier is somewhat wider in case of $W_2 = 0.4$ mm. Another feature which is worth mentioning is that $F_4$ can be seen in wider range in Figure 7 in spite of Figure 6. So, from these figures it can be inferred that $F_{p3}$ and $F_{p2}$ are merged together after a specific point of $(\theta_3 + \theta_4)/\theta_2$ and obviously this is subsisted for $F_3$ and $F_4$. In conclusion, it should be pointed out that for obtaining the most available resonant frequencies, then $(\theta_3 + \theta_4)/\theta_2$ should be chosen having a small value. However, $W_5$ can change the lower limit of the appearance frontier of additional resonant frequencies.

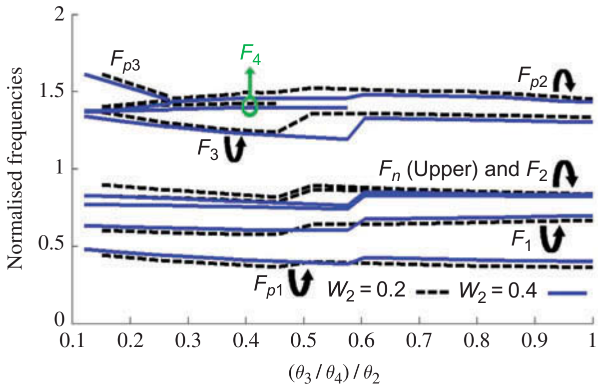


Figure 7. Resonant frequencies versus $(\theta_3 + \theta_4)/\theta_2$ while other parameters are: $L_1 = 4.8$, $L_2 = 6.6$, $W_1 = 0.8$, $W_3 = 1.6$, and $W_5 = 0.8$, unit: mm.

The most restriction can be seen in case of $F_{p3}$ because this resonant frequency exhibits more limited appearance frontier in comparison to $F_4$.

Now variation of $W_2$ / $W_3$ is investigated to understand filter performance. It is worth mentioning that accommodating all information into a picture was impossible and difficult to trace resonant frequencies behaviours. Therefore, these behaviours are illustrated in two figures. Figure 8 shows this variation when $W_5$ is set to 0.2 mm. The second passband consists of only a resonant frequency, i.e., $F_3$, and this is in conformity with Figure 2, as explained earlier. In this case, the filter cannot present a sharp slope at the upper stopband, as can be inferred from this figure. However, by increment of $W_2$ / $W_3$, filter can be sharper at the upper stopband and clearly lower stopband. Although $F_3$ is approximately fixed, the bandwidth of the first passband can be reduced by increment of $W_2$ / $W_3$; but lower stopband would be more selective. Figure 9 shows variation of $W_2$ / $W_3$ when $W_5$ is set to 0.8 and 1.6 mm. In this figure, the second passband exhibits two resonant frequencies, i.e., $F_3$ and $F_4$. This new resonant frequency, i.e., $F_4$, is very close to $F_{p2}$ under this specific condition. Therefore, by setting $W_5$ to 0.8 and 1.6 mm, the filter can

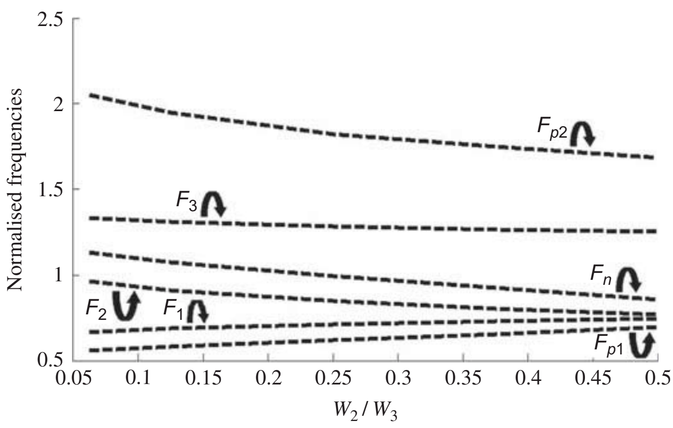


Figure 8. Resonant frequencies versus $W_2$ / $W_3$ while other parameters are: $L_1 = 4.8$, $L_2 = 6.6$, $W_1 = 0.8$, $W_3 = 1.6$, $L_3 = 1.6$, $L_4 = 1$, and $W_5 = 0.2$, unit: mm.

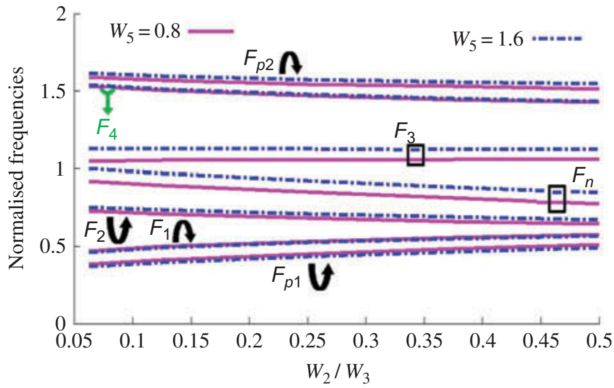


Figure 9. Resonant frequencies versus $W_2$ / $W_3$ while other parameters are: $L_1 = 4.8$, $L_2 = 6.6$, $W_1 = 0.8$, $L_3 = 1.6$, $L_4 = 1$, and $W_3 = 1.6$, unit: mm.

provide sharper slope at both the upper and lower stopbands. The increment of $W_5$ cannot increase the bandwidth of the first passband for values of near to 0.5 of $W_2$ / $W_3$. The bandwidth of the second passband is nearly fixed across the whole range of $W_2$ / $W_3$. In case of $W_5 = 0.2$ mm, $F_1$ and $F_2$ are more closer together for values of near to 0.5 of $W_2$ / $W_3$ in comparison with cases of $W_5 = 0.8$ and 1.6 mm.

## 2.2 *Full-wave analysis of the proposed filter*

Now, a wideband BPF with one notched bands based on the presented analysis in this section is offered. Displacement of notched band by variation of the stub with width of $W_5$ is investigated and full-wave simulation result is illustrated. The layout of the first filter is shown in Figure 1. The corresponding parameters are chosen as: $L_1 = 4$, $L_2 = 4.8$, $L_3 = 1.4$, $L_4 = 1.2$, $W_1 = 0.8$, $W_2 = 0.2$, $W_3 = 1.4$, and $W_5 = 0.2$ in mm on a substrate with a relative dielectric of 10.2 and thickness of 1.27 mm. Figure 10 shows the frequency response of the first BPF with a notched band. In Figure 11, variation of

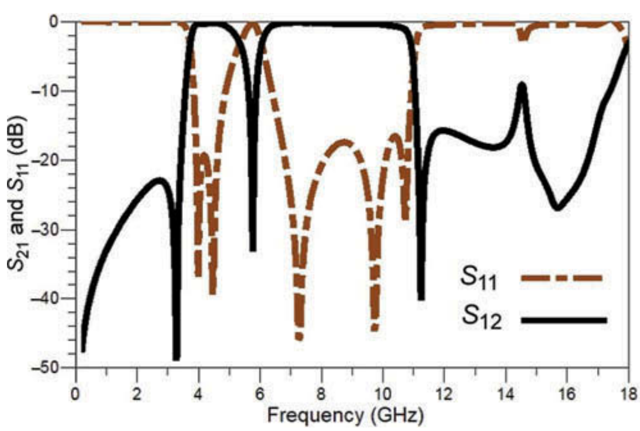


Figure 10. The first simulated filter with a notched band.

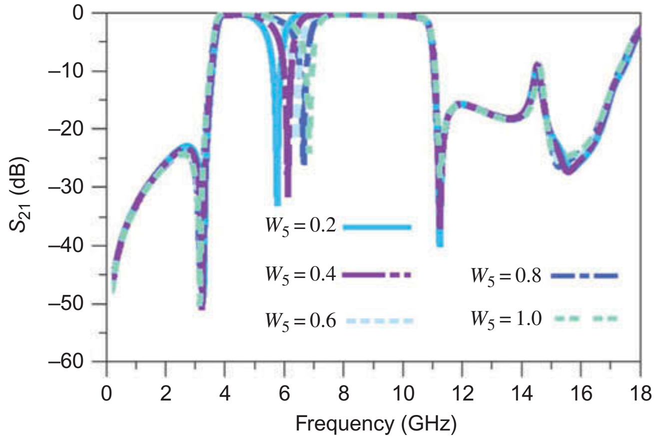


Figure 11. Investigation of displacement of notched band frequency with variation of $W_5$ while other parameters are fixed.



width of the stub with specified width of $W_5$ is investigated on displacement of notched band frequency of the first filter. It should be noted that to obtain this figure all other parameters of the first filter are fixed. In case of $W_5 = 0.2$ and $W_5 = 0.4$ the rejection level is better than –30 dB. For $W_5 = 0.2$ the notched band frequency is about 5.76 GHz while for $W_5 = 0.4$ is about 6.12 GHz. In case of $W_5 = 0.6$, this rejection level declines to –21.96 dB while for $W_5 = 0.8$ rejection level is about –26.09 dB. The centre of notched band frequencies for $W_5 = 0.6$ and $W_5 = 0.8$ are 6.38 GHz and 6.65 GHz, respectively. The rejection level and notched band frequency for $W_5 = 1.0$ are –24.2 dB and 6.83 GHz, respectively. Displacement of notched band frequency is about 0.36, 0.26, 0.27, and 0.18 GHz, respectively. Although steps of change of $W_5$ is equal, the frequency displacement does not obey this equality of steps. The second and third frequency displacement are very close together. By increase of $W_5$, the rejection level approximately declines. A disadvantage of the proposed filter is observed from this figure. For displacement of notched band frequency from 5.76 to 6.12 GHz, only a variation of 0.2 mm is required. Therefore, it may be difficult in practice to tune notched band frequency and obviously a precise fabrication tolerance may be required. On other hand, the proposed filter is capable of tuning notched band in the frequency range of 5.76–6.83 GHz, which is relatively a wide range while other parameters are constant. In case of $W_5 = 1.0$, the insertion loss at frequency of 10.75 GHz, at the end of passband, has degraded about –1 dB. Insertion loss is about –1 dB in cases of $W_5 = 0.2$ to $W_5 = 0.8$ at the frequencies of 10.69, 10.71, 10.69, and 10.71 GHz, respectively, which are approximately equal to each other.

Based on the proposed structure, the stub with width of $W_5$ by providing a new signal path, can cause a notched band (Kim & Chang, 2011). So, by providing the other signal paths, the other notched bands are possible. Design procedure of this second filter is very similar to the first one. It is expected that this is valid for displacement of the notched band frequency, too. Therefore, to avoid repeating similar descriptions only final parameters are provided in the next section.

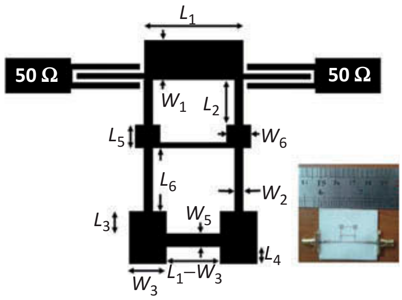


Figure 12. The layout of the second filter with two notched bands and the photograph of fabricated filter.



## 3. Measurement results and fabricated prototype

It is noteworthy that the most important problems that the authors were confronted with were the choice of substrate and dictation of minimum implementable width of 0.2 mm. Although, the presented analysis was based on a substrate with a relative dielectric of 10.2 and thickness of 1.27 mm, it was not possible to implement the filter by utilising this substrate. Obviously, this substrate change cannot alter filter design process and the presented analysis would be valid for other substrates, too. The presented analysis can provide information on how to design the proposed filter. Among limited available substrates for the authors, eventually, a substrate with a relative dielectric of 3.55 and thickness of 0.812 mm, Rogers RO4003, was chosen for fabrication to approve the discussed analysis. A substrate with high relative dielectric and more precise fabrication technology demands expensive implementation cost. Filter design process was followed to avoid demand of widths or gaps of lower than 0.2 mm. Final layout and fabricated sample of the second filter are shown in Figure 12. The final values are chosen as $L_1 = 9$, $L_2 = 3$, $L_3 = 1.1$, $L_4 = 1.1$, $L_5 = 1.4$, $L_6 = 4.2$, $W_1 = 0.4$, $W_2 = 0.2$, $W_3 = 2.0$, $W_5 = 0.2$, and $W_6 = 1.0$ all in mm. The width of the middle horizontal transmission line is 0.2 mm. Coupled line gap, width, and length are 0.2, 0.2, and 6.2 mm, respectively. With the aid of ADS software, method of moment (MOM) engine, full-wave simulation result is depicted in Figure 13. The simulation results exhibit that the first –3 dB passband is from 3.74 to 4.73 GHz while the second and third ones are from 5.76 to 7.62 GHz and from 8.48 to 10.3 GHz, respectively. Upper stopband is from 10.77 to 13.92 GHz with rejection of –20 to –34.66 dB. The rejection of the first notched band is about –39.64 dB at the frequency of 5.47 GHz. The second notched shows a rejection of –33.95 dB at the frequency of 7.94 GHz, too. The filter dimension is about $0.96\lambda_g \times 0.51\lambda_g$ where $\lambda_g$ is the guided wavelength at the centre frequency. The measurement result is illustrated in Figure 13 which shows a good agreement with simulation result. The second filter shows highly attenuated upper stopband, due to existence of an additional transmission zero at the frequency of 12.65 GHz, which can improve out-of-band performance. Therefore, the upper stopband rejection is from –25 to –52.9 dB in frequency band from 10.8 to 13.2 GHz. The first notched band is at 5.45 GHz while the second one is at the 7.95 GHz which are not far from the full-wave simulation results. The measured rejection level of the first and second notched bands are –21.77 and –20.82 dB, respectively. In addition, –10 dB FBW of these notched bands are about 7.34% and 5.03%, respectively.

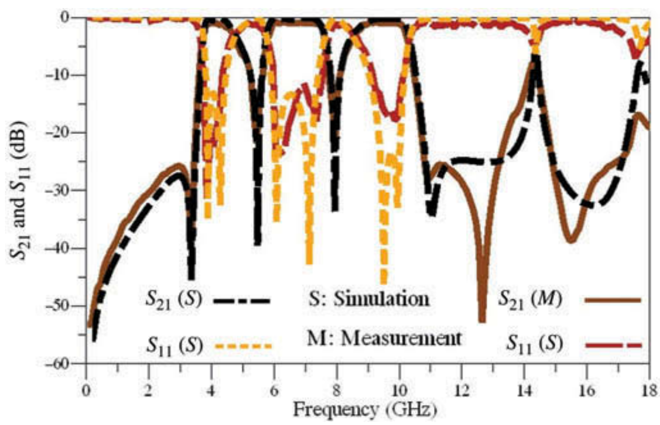


Figure 13. Measurement and simulation results of the second proposed filter.

Besides, the overall passband of the filter is from 3.68 to 10.2 GHz, which is very close to simulation results. Small frequency shift and other discrepancies can be attributed to the manufacturing process and loss of Sub-Miniature A (SMA) connectors. The vector network analyser E8361A of Agilent Technologies is used to test and measure the filter performance.

## 4. Conclusion

A wideband rectangular-ring resonator by using stepped-impedance resonator with multiple notched bands was proposed. The proposed filter is based on a low-cost technology of microstrip. Achievement of the notched bands with good rejection are possible without using any asymmetrical coupled lines approved by measurement results. Additional information on filter performance and design was provided to gain a better insight. Two wideband BPFs with one and two notched bands were designed. The notched band of the first filter is about 5.76 GHz with rejection of –33.16 dB and –10 FBW of 5.2%, as simulation results indicate. This notched band can be tuned from 5.76 to 6.83 GHz. The passband of this filter is between 4.1 and 10.9 GHz. In case of the second filter, the first notched band is at 5.45 GHz while the second notched band is at the 7.95 GHz. The measured rejection and –10 dB FBW for the first and second notched bands are –21.77, –20.82 dB, 7.34% and 5.03%, respectively. The upper stopband of the second filter is from 10.8 to 13.2 GHz with rejection of better than –25 dB. The second filter core size is about $0.96\lambda_g \times 0.51\lambda_g$.

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