Reconfigurable Bandwidth and Tunable Dual-Band Bandpass Filter Design for UWB Applications

Mushtaq Ahmed
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Reconfigurable Bandwidth and Tunable Dual-Band Bandpass Filter Design for UWB Applications

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ABSTRACT

Four square ring resonators together with an L-shaped uniform open tuning stub is the base of an ultra-wide bandpass filter. Based on the bandpass-coupled edge, a small gap was created in the feed lines of the proposed bandpass filter to obtain a second lower band. This study introduces a dual-band bandpass filter. The main advantage of this bandpass filter is its capability to reconfigure bandwidth and tune the center frequency of a dual-band bandpass filter function. The microstrip bandpass filter is reconfigured into a dual band when varactor diodes are fixed on the head of each uniform stub. The roll-off is characterized by sharp edges of 81.325 and 80.165 GHz/dB, which provided this filter with high selectivity in the transmission band, a wide stopband of more than 2 GHz in both sides, and a rejection band of up to 32 dB. Results show better performance of \( S_{21} \), which fluctuated from 4 to 1.5 dB within the transmission band from 8.327 to 13.942 GHz. All the reported filters were modeled, and their corresponding responses were assessed by using CST Microwave Studio (CST, 2010). Measured and simulated results of the proposed bandpass filters were compared, and the results indicate good agreement.

1. Introduction

Modern wireless communication systems are moving toward miniaturization and response controllability. New components should be able to take on these two roles. Microstrip ring resonators are one of the suggested solutions to meet the requirements of modern wireless communication systems. In this context, reconfigurable filters meet prerequisites regardless of topologies and mechanisms that are used (Hong & Lancaster, 2001; Hong, 2009; Ahmad & Minhad, 2013). Several well-known techniques are adopted to investigate these requirements (Wong & Hunter, 2008; Zhu et al., 2008; Tu, 2010; Miller & Hong, 2010; Rauscher, 2003; Chun & Hong, 2008; Nath et al, 2005; Al-Ahmad et al., 2007; Lugo & Papapolymrou, 2006; Abbaspour-Tamijani et al., 2003; Tang & Hong, 2011; Tsai et al., 2013; Arnold et al., 2014). One technique is bandwidth tunability, which results
from high intercoupling between resonators; resonator coupling can be controlled by using electronic components such as varactors, PIN diodes, or MEMS. Studies have addressed this problem by using different approaches, and some studies were able to achieve the goal of a specific center frequency (Wong & Hunter, 2008; Zhu et al., 2008; Tu, 2010). All the methods are used in narrowband applications. Other studies presented tunable bandwidth for wideband filter applications (Miller & Hong, 2010; Rauscher, 2003). However, problems in size and degradation as passband characteristics remain. Another technique is the tunable center frequency, which is achieved by altering the electrical length of the designed resonators. Among the approaches used to overcome relevant issues, the varactor diode is used for continuously tunable features (Chun & Hong, 2008; Nath et al., 2005; Al-Ahmad et al., 2007). The PIN diode is used for discrete center frequency (Lugo & Papapolymerou, 2006; Abbaspour-Tamijani et al., 2003). However, the tunable center frequency using the varactor diode exhibits distortion and dissipation losses in the transmission band, whereas the use of the PIN diode has less loss as its transmission characteristic. Finally, reconfigurable bandwidth and center frequency were presented in the same filter structure (Tang & Hong, 2011; Tsai et al., 2013; Arnold et al., 2014). The above studies demonstrate complex narrowband characteristics regarding design and high-cost effectiveness.

This study proposes a compact ultra-wide dual-band filter with good rejection and stopband. Low degradation in the RF signal is depicted in the output results. Up to the authors’ knowledge, this structure in ultra-wideband frequency range has been first demonstrated in this article. In this context, the edge coupled line and a tunable cap as a simple technique are used to achieve dual band and tenability. The authors try to make a balance between the simplicity in design and the efficient results. The introduced reconfigurable dual-band bandpass filter (BPF) can be employed in X-band applications. The simulated and measured results of the fabricated reconfigurable BPF prototypes are close to their appropriate extent.

2. The proposed filter design

Figure 1 shows the proposed microstrip filter configuration. A reconfigurable dual-band BPF with a separate tuning electronic semiconductor component is the objective of this work. The substrate Duroid Rogers RO5880 is used as a platform with dielectric thickness.
of 0.787 mm, a relative effective dielectric constant of 2.2, a loss tangent of 0.0009, and a copper thickness \( t \) of 0.0017 mm. The ground plane of this filter occupies the entire back face of the substrate. The microstrip filter consists of a main ring resonator that has a side length \( \ell_{\text{ring}} \) equal to 11.8 mm, which is equivalent to \( \approx \frac{\lambda_g}{2} \) at a center frequency of 11 GHz with a line width of 0.64 mm. Every side is folded from its ends up to \( \approx \frac{\lambda_g}{8} \) and then connected to the other sides, which results in the main ring resonators shown in Figure 1(a).

Main ring corners are completed to become four small square ring resonators, as shown in Figure 1(b). Furthermore, each side of the small square ring resonator is equal to 5.8 mm, which is equivalent to \( \lambda_g/4 \), and a line width of 0.64 mm at a resonant frequency of 11 GHz, which are calculated based on Eq. (1):

\[
f_0 = \frac{nc}{\lambda_g \sqrt{\varepsilon_{\text{eff}}}},
\]

where \( f_0 \) is the center frequency, \( n \) is the number of modes, \( c \) is the speed of light, \( \lambda_g \) is the guided wavelength, and \( \varepsilon_{\text{eff}} \) is the effective dielectric constant. In addition, two \( L \)-shaped uniform tuning open stubs are merged at \( \theta = \pm 45^\circ \) and \( \theta = \pm 135^\circ \) in all ring resonators with parameters \( \ell_{\text{stub}} = 2.84 \text{ mm}, \ell_{\text{stub1}} = 2.96 \text{ mm}, \) and \( w_{\text{stub}} = 0.486 \text{ mm} \) to obtain an ultra-wide BPF, as shown in Figure 2 (Hsieh & Chang, 2003).

The input/output feed lines with characteristic impedances of 50 \( \Omega \) are coupled directly to the main ring with a symmetric transmission line \( \ell_{\text{ring}} \) to reduce radiation and mismatch losses (Hsieh & Chang, 2003). The feed lines have a width \( w_{\text{fed}} \) of 1.79 mm. A gap width \( w_{\text{gap}} \) of 0.5 mm is created on each feed line, as shown in Figure 2. Based on this gap, a coupled-edge BPF was introduced as a second band. Finally, a microstrip capacitor (cap) was embedded in the feed lines of the proposed filter to adjust the

![Figure 2. Proposed dual-band BPF.](image)
generated lower band and to perform DC blocking in front of the DC current that comes from a vector network analyzer.

However, the new topology is still not intended for reconfigurability of response. On the other hand, numerous applications such as satellite links, wireless local networks, cellular telephones, synthetic aperture radars, and radio frequency identification systems, require dual-band filters. If the filter operates only at two bands or it operates over a finite BW at both of the bands, then it is known as a dual-band filter. The requirements of tunable and dual-band filters can be met using microstrip filters. And also, many modern communication systems are going to miniaturization and multi-functionality work. So, from these requirements, the dual-band filters as narrowband, wideband and UWB are highly required.

Motivated by these requirements, the authors used abrupt junction tuning varactor diodes, SMV1430 from Skyworks (n.d.) as electronic components to realize such a filter with a reconfigurable dual-band BPF characteristic. All varactor diodes are modeled in a microwave simulator (CST Microwave Studio; CST, 2010), similar to the practical case, to ensure that it will work as a variable capacitor. A reconfigurable dual-band BPF was achieved with good transmission and return loss responses together with miniaturization.

3. Reconfigurable bandwidth and center frequency of dual-band BPF performance

Figure 3 shows the modeling of the main ring resonator by using CST Microwave Studio (CST, 2010). The initial results of the proposed structure illustrate the bandpass characteristic with resonant pole frequencies in the ultra-wide band.

Afterward, four small square ring resonators were changed instead of the corners of the main ring resonator, as shown in Figure 1(b). This step means that upper and lower coupled ring resonator are connected in series, and then they are coupled in parallel to obtain an ultra-wide bandwidth, as expected in Chang (1996), with a compact size. The side length of the square ring resonator is designed to be equivalent to $\lambda_g/4$. Figure 4 shows the responses of the modified structure, which achieve ultra-wide stopband.
characteristics. Based on the orthogonality of the line side of the main ring to the small square rings, a bandstop response was achieved (Hsieh & Chang, 2003; Chang, 1996), which means that these transmission lines are the input/output feed lines of each square ring. In other words, the bandstop characteristics occurred because of odd mode excitation, which caused a short circuit in the system (Hsieh & Chang, 2003; Chang, 1996).

The uniform tuning open stubs, with small leg $\ell_{stub}$ of 2.84 mm, long leg $\ell_{stub1}$ of 2.96 mm, and line width $w_{stub}$ of 0.486 mm, were embedded in the other free sides of each square ring resonator to achieve ultra-wide BPF response, as shown in Figure 5 (Hsieh & Chang, 2003). The $L$-shaped uniform tuning open stub length is a quarter-guided wavelength ($\lambda_g/4$). The BPF structure was modeled under a full-wave electromagnetic simulator (CST Microwave Studio; CST, 2010). Using the optimization method based on this simulator, we extracted the response of the proposed BPF.

The following results were observed; a fractional bandwidth (FB) of 63.39% at 6 dB; five transmission poles at 7.4696, 8.8635, 10.932, 13.224, and 14.146 GHz. Moreover, the

Figure 4. Simulated $S$ parameter responses of the upgraded square ring resonators.

Figure 5. Simulated $S$ parameters of the proposed single-band BPF.
return loss is as poor as 6 dB at 7.8143 GHz and as good as 25 dB at 10.222 GHz. However, the transmission response displays 0.65 dB from 8.5992 GHz to 13.453 GHz and has transmission zeroes at \( f_{z1} = 6.4229 \) GHz, \( f_{z2} = 14.718 \) GHz, and \( f_{z3} = 16.145 \) GHz, with a broad stopband response of more than 2 GHz with high rejection level of up to 28 dB. The BPF response shows a good result, but a single bandpass response that resonates around 11 GHz is observed in Figure 6.

Referring to Hong and Lancaster (2001, p. 121), the authors created a small aperture of about \( 1/2\lambda_g \) away from the input/output port in the feed lines to get an edge-coupled BPF. Afterward, a cap of 1.9 pF was installed in the terminals of this aperture. The cap was used to adjust the response of the new lower band of the proposed dual-band BPF and to perform DC blocking to the DC current that comes from the vector network analyzer. The DC blocking capacitor prevents the DC current from affecting the varactor diodes.

Figure 2 was modeled and analyzed by using CST Microwave Studio (CST, 2010) to obtain the required dual-band with good performance. By using the optimization method, the authors extracted the transmission and the return loss responses, as shown in Figure 7.

![Figure 6. Simulated S parameters of BPF response of the proposed structure.](image1)

![Figure 7. Simulated S parameters responses of the proposed dual-band BPF.](image2)
The results imply the following: a dual-band pass response lower band resonates at 2.67 GHz with FB of 67.475% and one transmission pole at 2.67 GHz. Further, the upper band occurs at around 11 GHz with FB of 63.727%. Five transmission poles take place at 7.4895, 9.1139, 11.221, 12.744, and 13.822 GHz. The return loss has 6 dB at 7.827 GHz as the worst case and 18 dB at 12 GHz as the best case. Whereas the transmission response possesses 1 dB from 8.449GHz until 13.822 GHz with three transmission zeros at $f_{z1} = 6.434$ GHz, $f_{z2} = 14.916$ GHz, and $f_{z3} = 15.812$ GHz and offers a stopband of more than 2 GHz with a rejection band of up to 35 dB.

However, the presented dual-band BPF exhibited invariant S parameter characteristics. Avaractor diode was used to achieve the reconfigurable bandwidth and the tunable center frequency of the dual-band BPF, as shown in Figure 8.

4. Results and discussion

The proposed dual-band BPF illustrated in Figure 2 was modeled and analyzed at the designed center frequency of 11 GHz by using CST Microwave Studio (CST, 2010); the dielectric and metallic losses are considered in the simulation process. The conductivity of copper, $\sigma = 5.8 \times 10^7$ S/m, and the loss tangent, $\tan(\delta) = 0.0009$, of the substrate are employed in the simulation. At the resonant frequency, the side length of the small square ring resonator was set at 5.8 mm to be equivalent to quarter guided wavelength, which is given by Eq. (2):

$$\lambda_g = \frac{\lambda_0}{\sqrt{\varepsilon_{\text{eff}}}}.$$  (2)

where $\varepsilon_{\text{eff}}$ is the effective dielectric constant, and $\lambda_0$ is the free space wavelength (Hong & Lancaster, 2001; Pozar, 2009). The transmission line that connects each two square ring
resonators has a length $\ell_{\text{ring}}$ of 5.9 mm, which is equivalent to the quarter guided wavelength $\lambda_g$. The $L$-shaped tuning uniform open stub resonator with the mentioned length and width as shown in Figure 2, and the equivalent to quarter-guided wavelength was collected with each free side line of the small square ring resonator. Concurrently, Duroid Rogers’s substrate was used as a platform of the proposed dual-band BPF with a relative dielectric constant of 2.2 and a thickness of 0.787 mm. A standard-technology printed circuit board process was employed to fabricate the BPF, as shown in Figure 9.

The SMA connectors were connected to the input/output feed lines of the fabricated structure. Furthermore, a cap was soldered to the terminals of the etched aperture. Figure 10 shows a photograph of a fabricated dual-band BPF with the dimensions identified in Figure 2. The practical size of the proposed BPF was 23 mm $\times$ 23 mm. Moreover, the dual-band BPF provided two narrow and ultra-wide bands with good return loss and transmission responses. The proposed dual-band BPF is suitable for wide-frequency band applications, such as wireless systems, X-band applications, and satellite communications.

Figure 11 presents the simulated and measured results of the dual-band BPF in terms of transmission and reflection attributes. The measurement process was performed in an ordinary room environment by using a vector network analyzer (Anritsu 37347D). The simulated and measured responses agree best with each other, which validates the design flow. Furthermore, the fabricated dual-band BPF has two bands. The lower band resonated at 2.762 GHz with FB of 67.352% and one transmission pole at the resonated center frequency. The upper band has the following performance specifications: three transmission zeros ($f_{z1} = 6.434$ GHz, $f_{z2} = 14.682$ GHz, and $f_{z3} = 15.785$ GHz) and six transmission poles at 7.4895, 9.3425, 11, 12.574, 13.6362, and 14.4621GHz with FB equal to 63.683% at 3 dB. The roll-off offers a sharp edge of 81.325 GHz/dB (calculated from 7.2798 GHz with 3 dB to 7.1448 GHz with 30 dB) and 80.165 GHz/dB (calculated from 14.262 GHz with 3 dB to 14.4621GHz with 30 dB)
dB to 14.588 GHz with 30 dB), which provided this filter with high selectivity in the transmission band. There are wide stopband characteristics in both sides of more than 2 GHz with a rejection band of up to 32 dB. The result shows better performance of $S_{21}$, which fluctuated from 4 to 1.5 dB within the transmission band from 8.327 to 13.942 GHz. However, $S_{21}$ has some degradation of up to 5 dB at the transmission band. The return loss is 12 dB at 14.173 GHz as the lowest value and 17 dB at 11.673 GHz as the highest value during the passband from 7.2871 to 14.267 GHz at 6 dB.

Comparisons with other wideband BPFs are depicted in Table 1; it shows that the proposed wideband BPF has good performance. However, based on Table 1 as shown in below the insertion loss comparing with the others based on the methodology of design,
the simplicity, cost effective is regarded acceptable. On the other hand, based on the restricted requirements of modern communication systems the overall design and its results are convenient comparing with the other published structures and results.

A varactor diode-type SC-79 plastic packaged abrupt junction tuning varactor SMV 1430 from Skyworks was used as a variable reactive component (Skyworks, n.d.). The single package has capacitance values of 0.31 and 1.24 pF at 30 and 0-V bias, respectively, with a low series resistance of 3.15 Ω. The small resistance of these varactor diodes makes them appropriate for high-Q resonators in wireless systems. The varactor diode is used to alter the electrical length of each L-shaped uniform tuning open stub and varies the current distribution of each L-shaped uniform tuning open stub and varies the current distribution of the entire structure to obtain reconfigurable bandwidth, tunable center frequency, and dual-band BPF. The varactor diode was installed at the head of each uniform tunable open stub resonator, as shown in Figure 8. This procedure was modeled by using CST Microwave Studio (CST, 2010) because this procedure requires high machining techniques, which our laboratory cannot provide. However, the simulated results of the dual-band BPF were validated by the measured results of the fabricated dual-band BPF, which means that the CST simulator has a high confidence level and can be used to extract the S parameters of the modeling structure, as shown in Figure 8. Figures 12 and 13 display the transmission response $S_{21}$ and the return loss $S_{11}$ of the reconfigurable bandwidth and tunable center frequency of the dual-band BPF, respectively.

### Table 1. Comparison with other listed wideband BPFs.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Size (mm)</th>
<th>Band of applications</th>
<th>Return loss (dB)</th>
<th>Insertion loss (dB)</th>
<th>Stopband (GHz)</th>
<th>Roll-off (dB/GHz)</th>
<th>Dielectric constant/h (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rave et al. (2014)</td>
<td>25 × 25</td>
<td>X-band</td>
<td>12</td>
<td>2.4</td>
<td>1.5</td>
<td>16.66</td>
<td>3.55/0.5</td>
</tr>
<tr>
<td>Moitra et al. (2013)</td>
<td>40.92 × 11.57</td>
<td>Ku-band</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>49.33</td>
<td>3.48/0.51</td>
</tr>
<tr>
<td>Ain et al. (2010)</td>
<td>40 × 49</td>
<td>X-band</td>
<td>19.42</td>
<td>3.53</td>
<td>0.35</td>
<td>56.66</td>
<td>2.5/0.508</td>
</tr>
<tr>
<td>This work</td>
<td>23 × 23</td>
<td>X-band</td>
<td>17.35</td>
<td>1.5</td>
<td>3.5</td>
<td>81.325</td>
<td>2.2/0.787</td>
</tr>
</tbody>
</table>

**Figure 12.** Simulated $S_{21}$ of the reconfigurable bandwidth and tunable center frequency of dual-band BPF.
The dual band of the reconfigurable BPF shifted about 2 GHz compared with the invariant dual-band BPF. This shift occurred because the connected varactor, which changes the electrical length of the uniform tuning open stub, which led to the change in the resonant frequency of the entire structure, as shown in Eqs. (3) and (4):

\[ \ell_r = n\lambda_g, \]  

\[ f_o = \frac{nc}{\lambda_g \sqrt{\varepsilon_{eff}}}, \]  

where \( \ell_r \) is the physical length of the resonator, and \( f_o \) is the center frequency of the designed structure.

Figure 12 depicts the transmission responses of the reconfigurable bandwidth and tunable center frequency dual-band BPF. The simulated results of the lower passband show a constant fractional-bandwidth range of 48 ± 8% at 6 dB. The corresponding center frequency changes from 4.62 to 6.2 GHz with an insertion loss of 0.6655 to 0.555 dB, while the bias voltage changes from 30 to 0 V. Further, the upper band exhibits an insertion loss of 1.2 dB from 11.337 to 14.784 GHz. The upper side band of the upper frequency band is almost unchanged, whereas the lower edge is reconfigured from 9.843 to 10.876 GHz at 6 dB. The bias voltage of 0 to 30 V is applied to the varactor diode, and the wide stopband is observed at more than 2 GHz with the rejection band above 25 dB. Moreover, the roll-off in almost reconfigurable bands is a sharp response of 81.325 GHz/dB, which provides this reconfigurable BPF with high selectivity that is suitable for wireless systems.

Figure 13 shows the return loss of the proposed reconfigurable dual-band BPF. The lower band was provided with a tunable center frequency of 5.49, 4.9852, and 4.5621 GHz at the variable capacitor of the varactor diodes of 0.31, 0.56, and 1.24 pF, respectively. The return loss of all bands ranges from 17 to 19 dB with two transmission poles. All the mentioned bands are appropriate for wireless communication systems. The upper band shows an almost invariant frequency at the upper edge, whereas the lower side shows a reconfigured frequency.
The return loss varies from 10 to 30 dB, which corresponds to the change of the capacitance of the varactor diode from 0.31 to 1.24 pF. Finally, the proposed reconfigurable bandwidth and tunable center frequency of the dual-band BPF is introduced as a good candidate for X-band applications, radar systems, and various types of wireless communication systems.

5. Conclusion

This study proposed a compact ultra-wide dual-band ring resonator with good rejection and stopband filter. A series-shunt configuration of the square ring resonator was used, and a uniform tunable open stub with a quarter-guided wavelength was designed. Both structures were integrated to provide an ultra-wide BPF. A gap was created in both input and output feed lines to validate the lower bandpass frequency band because of edge-coupled BPF theory. To adjust the specifications of the lower band and to prevent the DC current from the vector network analyzer from affecting the varactor diodes, the authors affixed a cap to the terminals of these gaps.

The following measurement results were found: the lower band resonates at 2.762 GHz with FB of 67.352% and one transmission pole at the resonated center frequency. The results reveal that the upper band has the following performance metrics: three transmission zeros \( f_{z1} = 6.434 \text{ GHz}, f_{z2} = 14.682 \text{ GHz}, \) and \( f_{z3} = 15.785 \text{ GHz} \) and six transmission poles at 7.4895, 9.3425, 11, 12.574, 13.6362, and 14.4621 GHz. Moreover, the FB is equal to 63.683% at 3 dB, and the roll-off leads to sharp edges of 81.325 and 80.165 GHz/dB, which provides this filter with high selectivity in the transmission band. Furthermore, the filter offers wide stopband characteristics on both sides of more than 2 GHz with a rejection band of up to 32 dB. The result shows better performance of the transmission band and return loss during the passband of the proposed BPF. Simulated and measured results validate the effectiveness of the proposed microstrip dual-band BPF. Comparisons between the simulated and measured results of the reconfigurable fabricated BPF prototype indicate good agreement. The introduced reconfigurable dual-band filter can fulfill the requirements of X-band applications, wireless systems, and satellite communications.

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