Design and optimisation of narrow dual bandpass filter using bell-shaped structure for RF receiver system

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Abstract: A novel approach for designing a narrow dual Bandpass Filter (BPF) using microstrip Coupled-Line Resonator (CLR) is presented in this paper. The proposed CLR consists of butterfly radial stub and 45° mitred bending with new ‘bell’-shaped structure. The proposed BPF consisting of two fundamental resonant modes with the resonant characteristic has been investigated using ADS software. To validate the design and analysis, the dual BPF was fabricated and measured. It is shown that the measured and simulated performances are in good agreement. A dual-band response BPF that operates at 2.4 GHz and 5.75 GHz is designed and implemented for wireless applications.

Keywords: dual BPF; bell-shaped structure; microstrip coupled line; butterfly radial stub; mitred bend.


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1 Introduction

Bandpass filters (BPF) play a significant role in wireless communication systems. Transmitted and received signals have to be filtered at a certain centre frequency with a specific bandwidth. Recently, different approaches have been introduced for the design of dual BPFs. Guo and Yang (2017) presented a dual BPF wide stopband filter with rotational symmetry using composite right/left-handed resonators. The simplest way to construct a dual BPF is combining two single band filters at different passband frequencies (Chen and Hsu, 2006). However, they have the double size and cost of a single band filter. Alternatively, the dual BPF can be achieved by U-shaped resonators using only coupling between adjacent resonators without cross-couplings (Ogbodo et al., 2016). The circuit size is still larger since two filter sections are also needed. Dual BPF can also be realised by combining two sets of resonators with common input and output (Chen and Hsu, 2006). Besides utilising two or more resonators, a dual BPF can be designed by using a Stepped-Impedance Resonator (SIR) (Zhu and Abbosh, 2016). Nevertheless, this power capacity of BPF needs to be improved. Other filters reported in coupled-line section width and gap are so tight from 0.1 mm
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Motivations for this filter design are to address the characteristics of coupled line, butterfly radial stub, and mitred bend in order to elaborate their applications to possible new filter configurations and also to meet the output requirements of the wireless system standard. Theories and techniques are to be described to extract the parasitic elements in our new model filter. The filter demonstrates better S-parameters and group delay performance as well as compact fabrication size.

2.2 Butterfly radial stub

Butterfly Radial Stub (BRS) has been widely used in many microwave circuits such as filters, matching networks, bias lines even grounding RF signal. According to bell-shaped structure in Figure 1, the BRS is connected parallel to the transmission path. The geometry of BRS is based on the
A combination of two radial stubs as shown in Figure 3 (a). In Figure 3 (b), the ends of the feed lines are referenced to the centre of the radial stub. The penetration depth \( P \) may exceed the width of the microstrip feed line. The widths of the stub base \( W \) and \( P \) are related by the formula as equation (6).

\[
W = 2 \times P \times \tan\left(\frac{\vartheta}{2}\right) \tag{6}
\]

The angle \( \vartheta \) is limited to a range from \( \vartheta_{\text{min}} < \vartheta < 170^\circ \) in order to avoid sizes which do not make sense. From Figure 3 (c), the variations of inductance \( L \) and capacitor \( C \) circuit also can be observed and it depends on the dielectric substrate and mainly on \( R_o \) and \( \vartheta \) as mentioned in equations (7) and (8) (March, 1985).

\[
L = \frac{120\pi h}{\vartheta} \left[ \ln\left(\frac{R_o}{R_i} - \frac{1}{2}\right) \right] H \tag{7}
\]

\[
C = \frac{\vartheta R_o^2 \varepsilon_{\text{eff}}}{240\pi hc} F \tag{8}
\]

A BRS is an open circuit stub realised in radial transmission line instead of straight transmission line. It is a very useful element, primarily for providing a clean (no spurious resonances) broadband short circuit, much broader than a simple open circuit stub. It is especially useful at high frequencies. Figure 4 shows the optimising of the value \( \vartheta \) at 5.75 GHz.

According to Figure 4, when \( \vartheta \) is less than \( \vartheta_{\text{opt}} \), the frequency resonance \( (S_{21}) \) at the high frequency band is shifted to the left, if \( \vartheta \) is larger than \( \vartheta_{\text{opt}} \), the frequency resonance is shifted to the right. The \( \vartheta \) value decreases or increases by interval 1° to show the effectiveness of the filter performance. The \( S_{11} \) also keep tracking respectively when \( S_{21} \) are shifted. Based on the result, it also found that the low frequency responses (2.4 GHz) remain at the initial condition without any changes. It shows that the high frequency can be varied and the low frequency is locked from amendment. As mentioned before, the \( \vartheta \) should not be more than 170° to ensure the size makes sense.

2.3 Mitred bending (discontinuity)

There are several types of bend configuration such as outer cut-off bend, 90° bend or 45° mitred bend with different width \( W \). Each bending will be connected with 50Ω input and output transmission line. Figure 5 shows each bending type being tested and plotted by simulating the \( S_{11} \) and \( S_{21} \) outputs for the comparison. This bending circuit is installed with FR4 microstrip line with a substrate thickness of 1.6 mm, a dielectric constant \( \varepsilon_r \) of 4.4, a loss tangent of 0.019 and a copper thickness of 0.035 mm.
The configuration of Figure 5 which was 45° mitred bend (‘*’ symbol) provides the best compensation based on $S_{11}$ and $S_{21}$ with other bends types. When laying out microstrip transmission lines an abrupt bend of 90° can cause a significant portion of the signal on the strip to be reflected back towards its source. This results in only a portion of the signal passing through and causes unwanted reflections in the system which degrades performance. Mitring the bend is one of the ways in which the reflections can be reduced. A 90° bend in a transmission line adds a small amount of capacitance to the transmission line, which causes a mismatch. A mitred bend reduces some of that capacitance, restoring the line back to its original characteristic impedance. Figure 6 shows the 45° mitred bend. A good example (Hsieh and Chang, 2003) was verified of new parameter in ring resonator with improved $S$-parameters. The ring resonator was 45° mitred bend and simulated to optimise its resonant frequency.

In the bell-shaped structure, the microstrip coupled line was matched with butterfly radial stub to provide two resonances at high and low frequency. The terminations of 50Ω feeder and the coupled line were linked by discontinuity of 45° mitred bend. It found that the 45° mitred bend provides a maximum bandwidth of the $S_{21}$ and excellent $S_{11}$ compared to other bending types (Razalli et al., 2008). Figure 7 shows the bell-shaped structure has a symmetrical design, thus all parasitic elements can be extracted from only one side of the equivalent circuit. $L$ and $C$ are the parasitic elements (bending circuit), $l$ and $w$ are line widths of the stubs connecting transmission and feeder.
The physical dimensions of the proposed dual BPF bell-shaped structure are as shown in Table 2. Each dimension at the left side is equal to the right side of symmetry axis. The length and width have been optimised with ranges of 0.5 mm to 14 mm. It should be noted that the parameter $\theta_{opt}$ (69.9°) is chosen from BRS for adjustable the high band resonance.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Item for</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_1$</td>
<td>50Ω feeder microstrip length</td>
<td>7 mm</td>
</tr>
<tr>
<td>$l_2$</td>
<td>Coupled-line length</td>
<td>14 mm</td>
</tr>
<tr>
<td>$l_3$</td>
<td>Microstrip length</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>$l_4$</td>
<td>Taper microstrip length</td>
<td>1 mm</td>
</tr>
<tr>
<td>$w_1$</td>
<td>Microstrip width</td>
<td>1 mm</td>
</tr>
<tr>
<td>$w_2$</td>
<td>Taper microstrip length</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>$s$</td>
<td>Separation gap</td>
<td>1 mm</td>
</tr>
<tr>
<td>$\theta$</td>
<td>69.9°</td>
<td>Butterfly radial stub</td>
</tr>
<tr>
<td>$w_3$</td>
<td>2 mm</td>
<td></td>
</tr>
<tr>
<td>$R_o$</td>
<td>2.21 mm</td>
<td></td>
</tr>
<tr>
<td>$D$</td>
<td>1.21 mm</td>
<td></td>
</tr>
</tbody>
</table>

### 3 Results

The simulations graph for bell-shaped structure is depicted in Figure 8. The results show that the transmission is –2.074 dB and –3.264 dB and the reflected factor is –14.930 dB and –14.765 dB at 2.4 GHz and 5.75 GHz, respectively. It is seen that the filter has a bandwidth of 220 MHz within frequency from 2.28 GHz to 2.5 GHz and 440 MHz within frequency from 5.49 GHz to 5.93 GHz at –3 dB of the peak response. The BPFs measurement is shown in Figure 9. The design is measured using PNA-X Network Analyser from Agilent Technologies. Figures 9 (a) and 9 (b) show the outputs of transmission are –8.25 dB and –7.92 dB and the reflected factors are –13.89 dB and –12.71 dB at 2.4 GHz and 5.75 GHz respectively. Both bandwidths measured within –3 dB of the response at its peak and obtained 490 MHz and 390 MHz at 2.4 GHz and 5.75 GHz.

Figure 10 shows the dual BPF of group delay simulation. The difference between high and low frequency group delay is 1.83 ns and 1.23 ns from mid-band frequency group delay at 0.18 ns.

The filter fabrication is realised by using standard photolithography process on FR4 substrate microstrip. The advantages of microstrip technology include simplicity, small size, light weight and durable finish as compared to conventional design (Ahmad et al., 2015). These advantages are significant for smaller size RF components design, nowadays. The fabricated prototype of this dual BPF is depicted in Figure 11. Two 50Ω terminal lines are extended to accommodate the SMA connectors to connect to the Vector Network Analyser (VNA) for measurement. This prototype filters with a small compact size of 2.5 cm × 2.5 cm.
Both simulation and measurement achieved the target requirements. Table 3 shows the comparison of simulation and measurement parameters for dual BPFs. By comparing the measurement with the simulation bandwidth results, the differences are 55.1% for 2.4 GHz and 12.8% for 5.75 GHz.

Table 3  Simulated and measured results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Simulation</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
<td>2.4 5.75</td>
<td>2.4 5.75</td>
</tr>
<tr>
<td>Bandwidth (MHz)</td>
<td>220 440</td>
<td>490 390</td>
</tr>
<tr>
<td>Transmission, $S_{21}$ (dB)</td>
<td>-2.074 -3.264 -8.250 -7.920</td>
<td></td>
</tr>
<tr>
<td>Reflectd, $S_{11}$ (dB)</td>
<td>-14.930 -14.765 -13.89 -12.710</td>
<td></td>
</tr>
</tbody>
</table>

4 Conclusion

In this paper, bell-shaped structure filter with utilising transmission CLR, butterfly radial stub and 45° mitred bends technique is designed. This filter helps to achieve better $S_{11}$ and $S_{21}$ at the resonant bands of 2.4 GHz and 5.75 GHz. This filter not only delivers better $S$-parameters than others (Chen and Hsu, 2006; Alkanhal, 2009; Wu et al., 2008) but also saves as much compact circuit size compared with previous designs. The experimental verification also indicates how close the simulation results and measurements are. This project contributes to build a part of the dual-band concurrent RF front-end receiver with a dual channels output.

References


