Novel ultra-wideband (UWB) bandpass filter using multiple-mode resonator

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Abstract: A novel compact microstrip ultra-wideband (UWB) bandpass filter (BPF) is proposed using a multiple-mode resonator (MMR), aiming at transmitting signals in the whole UWB passband. The resonant frequencies of this MMR in the design are properly adjusted equally within the UWB passband. Then, two aperture-backed interdigital coupled-lines at the two sides are introduced for an effective enhancement of the capacitive coupling factor. Transmission zeros can be created at the lower and upper passband edges to improve the passband selectivity greatly. Finally, a microstrip UWB filter with good in-band filtering performance and sharp rejection skirts is simulated and fabricated with good agreement.

Keywords: ultra-wideband (UWB), bandpass filter (BPF), multiple-mode resonator (MMR), resonant frequency

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

1 Introduction

Since the Federal Communication Commission released the unlicensed frequency band of 3.1–10.6 GHz for commercial ultra-wideband (UWB) systems in 2002, the UWB technology has great potential in the development of various modern transmission systems, such as, medical imaging, through-wall imaging indoor, and hand-held UWB systems. A tremendous interest in the exploration of UWB bandpass filters (BPFs) with good in-band transmission and out-of-band rejection performances has been aroused. Recently, various new structures and design methods have been used to develop new UWB bandpass filters, such as composite lowpass-highpass filter topology [1], coupled-line structure [2], planar balun [3], cross coupling structure [4], transversal signal-interaction [5] and multiple-mode resonators (MMRs) [6, 7, 8, 9, 10, 11, 12, 13]. The multiple-mode resonator was originally used to design the UWB filter in [7]. It consists of stubs-loaded MMR at the center section and two identical coupled-lines located at the left and right side, but it suffered from high insertion loss and worse selectivity. Then, some modified and new kinds of MMR were proposed. In [8], three open-ended stubs were loaded at the center of a stepped-impedance resonator to allocate the resonant modes more closely. By using open stub and short stub at the center in [9], the even modes can be tuned easily whereas the odd modes are fixed. In [10], the stepped-impedance stub loaded resonator was used, and the designed UWB filter has good filtering performance.

In this paper, a novel compact microstrip UWB bandpass filter using a modified multiple-mode resonator is presented. The configuration of the proposed UWB BPF is shown in Fig. 1. The resonant frequencies of this MMR in the design are properly adjusted equally within the UWB passband. Two aperture-backed interdigital coupled-lines at the two sides are introduced for an effective enhancement of the capacitive coupling factor. Transmission zeros can be created at the lower and upper stopband to achieve good skirt selectivity and harmonic suppression. The measured results are in good agreement with simulated predictions, showing good wideband filtering performance with sharp rejection skirts.

2 Analysis on the proposed resonator

Fig. 1 illustrates the topology of the presented microstrip UWB bandpass filter. As depicted in Fig. 1, the multi-mode resonator consists of two ring resonators and a short stub loaded at the upper ring resonator. Two identical \( \lambda_g/4 \) high-impedance line sections are at the two sides, where \( \lambda_g \) is the guided wavelength of the 50Ω line at the central frequency of the UWB passband. By properly optimizing the structure, a UWB filter with good wideband performance and sharp rejection skirts is explored. The substrate used in this structure is commercial with a relative
dielectric constant of 2.55 and a thickness of 0.8 mm. The equivalent transmission line network of the proposed UWB filter is shown in Fig. 2, in which the interdigital coupled-line can be equaled as a J-inverter susceptance in the middle and two single transmission lines at the two sides.

Since the MMR is symmetrical in structure, even- and odd-mode analysis method could be applied in the analysis of resonant modes. The central plane of this modified MMR with symmetrical structure represents a perfect electric wall or short circuit for all the odd-order resonant modes, while it indicates a perfect magnetic wall or open circuit for all the even-order modes. The configuration and conventional denotation of the proposed resonator is shown in Fig. 3(a). Fig. 3(b) and (c) represents the even-mode and odd-mode equivalent circuit, respectively. For simplicity, we neglect the via inductances effects and the parasitic fringe capacitances.

For the even-mode equivalent circuit in Fig. 3(b), the even-mode input admittance $Y_{\text{even}}$ can be expressed as:

$$
Y_{\text{even}} = Y_c + j \cdot \left( Y_1 \tan \theta_1 + j Y_3 \tan \theta_3 + j Y_2 \frac{Y_2 \tan \theta_2 \tan \theta_4 - Y_4}{Y_2 \tan \theta_2 + Y_4 \tan \theta_2} \right). 
$$

From the condition $Y_{\text{even}} = 0$, the resonance frequencies of the even excitation in Fig. 3(b) can be extracted as:

$$
Y_1 \tan \theta_1 + Y_3 \tan \theta_3 + Y_2 \frac{Y_2 \tan \theta_2 \tan \theta_4 - Y_4}{Y_2 \tan \theta_2 + Y_4 \tan \theta_2} + Y_c \tan \theta_c = 0. 
$$

For the odd-mode equivalent circuit in Fig. 3(c), the odd-mode input admittance $Y_{\text{odd}}$ is written as:

$$
Y_{\text{odd}} = Y_c + j \cdot (-j Y_1 \cot \theta_1 - j Y_2 \cot \theta_2 - j Y_3 \cot \theta_3) + Y_c \tan \theta_c. 
$$
From the condition $Y_{odd} = 0$, the resonance frequencies of the odd excitation in Fig. 3(c) can be extracted as:

$$-Y_1 \cot \theta_1 - Y_2 \cot \theta_2 - Y_3 \cot \theta_1 + Y_c \tan \theta_c = 0.$$ \hspace{1cm} (4)

It is evident from (2) and (4) that resonance conditions can be controlled by adjusting the structural parameters of the resonator for both even and odd modes. Meanwhile, the frequency-dependent transmission response of the proposed MMR with varied $L_4$ and $L_5$ under weak coupling is shown in Fig. 4. We can observe that there are three resonances in the UWB frequency band. It can be seen that when $L_4$ varies from 2.5 to 3.5 mm, and $L_5$ varies from 1 to 2 mm, the first and third resonant modes move towards the lower frequency without disturbing the second mode. By properly adjusting the structural dimensions of the MMR, the resonant frequencies can be easily allocated.

Table I presents the calculated and EM simulated results of the resonator with determined structural parameters. The first three resonant frequencies are of our concern. Both results are consistent with each other. The discrepancy might be due to the effect of parasitic capacitances and via inductances neglected in the equivalent circuit and dispersion of microstrip.

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>$f_{c1}$</th>
<th>$f_{c1}$</th>
<th>$f_{c2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated</td>
<td>3.37</td>
<td>5.88</td>
<td>8.53</td>
</tr>
<tr>
<td>EM-simulated</td>
<td>3.43</td>
<td>6.02</td>
<td>8.81</td>
</tr>
</tbody>
</table>

Based on the above analysis, if this MMR is properly fed with increased coupling strength using interdigital coupled lines, a UWB passband can be realized while the in-band resonant peaks remain nearly unchanged. Meanwhile, aperture-
backed coupling structure by removing an area on the ground plane can raise the coupling degree while relaxing the line space. Fig. 5 shows the simulated response of the resonator with varied $L_1$. Two transmission zeros are generated at 0 and $2f_0$ by parallel coupled lines whose length is quarter-wavelength ($\lambda_0/4$) at center frequency $f_0$ of the passband. In addition, the signal transmitted from port 1 to port 2 is mainly through three ways in the resonator, which is shown as $2\theta_2$, $2\theta_1$, 

![Fig. 4.](image)

(a) Simulated response of the proposed MMR under weak coupling versus different $L_4$. (b) Simulated response of the proposed MMR under weak coupling versus different $L_5$.

![Fig. 5.](image)

Fig. 5. Frequency-dependent $S_{21}$ of the proposed MMR versus different $L_1$. 
The electrical lengths of the three paths at 0.25 GHz are respectively 3.53, 1.48 and 2.06 degree. The difference of electrical lengths between the two paths of $2\theta_1$ and $2\theta_3$ is nearly 0.5. Then, a transmission zero at 0.25 GHz will be generated due to the phase cancellation. The upper cutoff frequency and transmission zero moves to lower frequency when $L_1$ is increasing.

Thus, the two side length of the ring resonator and the short circuited stub can provide a high degree of freedom to adjust the locations of the first three resonant frequencies in the UWB spectrum. By applying the parallel-coupled feed lines with two aperture-backed at the two sides to the proposed MMR, an UWB BPF with simple structure, compact size and good passband performance is realized.

### 3 Filter design and experimental result

A prototype was fabricated on a commercial substrate with a relative dielectric constant of 2.55 and a thickness of 0.8 mm. Fig. 6 is the photograph of the fabricated UWB filter.

![Photograph of the fabricated UWB filter.](image)

The structural parameters for the UWB BPF circuit are: $W_1 = 2.2\, \text{mm}$, $W_2 = 0.2\, \text{mm}$, $W_3 = 0.2\, \text{mm}$, $W_4 = 0.3\, \text{mm}$, $W_5 = 0.2\, \text{mm}$, $W_6 = 0.3\, \text{mm}$, $W_7 = 0.3\, \text{mm}$, $W_8 = 0.3\, \text{mm}$, $W_9 = 0.3\, \text{mm}$, $W_{10} = 2.2\, \text{mm}$, $L_1 = 8\, \text{mm}$, $L_2 = 8\, \text{mm}$, $L_3 = 1.8\, \text{mm}$, $L_4 = 2.7\, \text{mm}$, $L_5 = 0.7\, \text{mm}$, $L_6 = 3.6\, \text{mm}$, $L_7 = 8.2\, \text{mm}$, $R = 0.25\, \text{mm}$.

Although a low dielectric constant has been used, the circuit size of the UWB filter is extremely compact with a size of $20\, \text{mm} \times 4.3\, \text{mm}$, which amounts to only $0.58 \lambda_0 \times 0.12 \lambda_0$, where $\lambda_0$ is the guided wavelength of the 50$\Omega$ line on the substrate at the midband frequency. Fig. 7 shows the simulated and measured results of the fabricated filter.

Good agreement between the simulated and measured results is observed. It can be seen that the fabricated UWB BPF has good in-band filtering performance with insertion loss less than 1.2 dB and return loss better than 11 dB. The 3 dB passband covers the range of 2.5–11.1 GHz, and the fractional bandwidth is 126%. In addition, the flat group delay in the passband is achieved with a maximum variation of less than 0.2 ns, showing a good linearity. The deviations between simulation and measurement might be due to the parasitic effects of the SMA connectors and the fabrication error, as well as other uncertainties. It can be improved by more careful fabrication and measurement technology. Comparison with other prior UWB BPFs is shown in Table II, which depicts that the UWB filter has advantages in size and stopband performance.
Conclusion

In this paper, a novel compact microstrip UWB BPF has been proposed and designed using a multiple-mode resonator. The resonant frequencies of this MMR in the design are properly adjusted equally within the UWB passband. Two aperture-backed interdigital coupled-lines are introduced for an effective enhancement of the capacitive coupling factor. Good agreement was obtained between the simulation and the measurement results. Due to its simple topology, compact size and satisfactory performance, the proposed filter can be practically applied in the modern UWB communication systems.

Acknowledgments

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Table II. Comparison with some reported UWB BPFs

<table>
<thead>
<tr>
<th>Ref.</th>
<th>$\varepsilon_r$/height (mm)</th>
<th>FBW (3 dB)</th>
<th>S.F. $S.F. = \frac{\Delta f_{13dB}}{\Delta f_{130dB}}$</th>
<th>$f_c$ (GHz)</th>
<th>Size: $(\lambda_0 \times \lambda_0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[2]</td>
<td>2.2/0.508</td>
<td>117%</td>
<td>0.499</td>
<td>13.5</td>
<td>0.44 x 0.11</td>
</tr>
<tr>
<td>[3]</td>
<td>2.65/0.5</td>
<td>110%</td>
<td>/</td>
<td>12.5</td>
<td>1.01 x 0.95</td>
</tr>
<tr>
<td>[4]</td>
<td>2.45/0.8</td>
<td>108%</td>
<td>0.804</td>
<td>12</td>
<td>0.63 x 0.46</td>
</tr>
<tr>
<td>[5]</td>
<td>2.65/0.5</td>
<td>110%</td>
<td>0.855</td>
<td>11.2</td>
<td>1.01 x 0.51</td>
</tr>
<tr>
<td>[7]</td>
<td>10.8/1.27</td>
<td>113%</td>
<td>0.642</td>
<td>13</td>
<td>1.07 x 0.14</td>
</tr>
<tr>
<td>This work</td>
<td>2.55/0.8</td>
<td>126%</td>
<td>0.802</td>
<td>15</td>
<td>0.58 x 0.12</td>
</tr>
</tbody>
</table>

$\lambda_0$ is the free space wavelength at 6.85 GHz; S.F. is the skirt factor of the passband; $\Delta f_{13dB}$, $\Delta f_{130dB}$: 3 dB bandwidth and 30 dB bandwidth of the passband, respectively; $f_c$ is the upper stopband frequency with 20 dB attenuation.

4 Conclusion

In this paper, a novel compact microstrip UWB BPF has been proposed and designed using a multiple-mode resonator. The resonant frequencies of this MMR in the design are properly adjusted equally within the UWB passband. Two aperture-backed interdigital coupled-lines are introduced for an effective enhancement of the capacitive coupling factor. Good agreement was obtained between the simulation and the measurement results. Due to its simple topology, compact size and satisfactory performance, the proposed filter can be practically applied in the modern UWB communication systems.