An Enhanced Skirt Characteristics Triple-Mode Filter

Jahyeon Lee¹ · Hun Nam² · Yeongseog Lim¹

Abstract

This paper presents a compact microstrip triple-mode filter with enhanced skirt characteristics. The presented triple-mode filter configuration supports three transmission poles and three transmission zeros within the nearby passband. Two of transmission zeros are generated by a triple-mode resonator itself, and the third one is generated by small cross-couplings between the I/O ports. Each resonance condition and the transmission zero generation conditions are analyzed using an equivalent circuit. The bandpass filter is designed for a 2.4 GHz WLAN. The filter was fabricated with a relative dielectric constant of 3.5 and a thickness of 0.76 mm. The fabricated filter has a small size (7.9 mm×7.2 mm, i.e., 0.107 λg×0.098 λg, where λg is guided wavelength at a center frequency) and shows high performing skirt characteristics.

Key words: Resonator Filters, Microstrip Filters, Band Pass Filters, Triple-Mode.

I. Introduction

The microstrip dual-mode filter has become one of the most significant planar filters, as each resonance mode can be used as a doubly tuned circuit. Therefore, the number of resonators that are required for a given filter degree is halved, resulting in a reduced-size filter structure. The dual-mode microstrip resonator was first proposed by Wolff [1]. Since then, various types of dual-mode resonators have been proposed [2]∼[8]. In [2]∼[4], a perturbation is applied on a closed loop resonator; in [5]∼[6], a short- or open-stub is applied on a half-wave open loop resonator; in [7] a hybrid resonant circuit was proposed by using a combination of a series and shunt resonant circuit; and in [8], a short-circuited stub and an interdigital capacitor were added to a half-wave stepped impedance. These dual-mode resonators commonly generate one or two transmission zeros themselves, such as open stub effects. Subsequently, some triple-mode filters with high frequency selectivity have been presented [9]∼[13]. A λ/2 transmission line resonator with a pair of center-loaded stubs is used for the design of triple-mode filters. The design of a compact triple-mode filter with high-performance characteristics is still a challenge.

In order to solve this problem, we proposed a compact triple-mode resonator for a triple-mode filter [15]. This triple-mode resonator is constructed on a half-wave stepped impedance resonator by the addition of an interdigital capacitor and two short-circuited stubs. This structure can support three resonances; i.e., one resonance is supported in an odd mode and the other two resonances are supported in an even mode. In a filter application, a triple-mode filter has just one transmission zero within its nearby passband, and it shows poor skirt characteristics. The skirt characteristics of the triple-mode filter need to be enhanced.

In this paper, we present a triple-mode filter with skirt characteristics that have been enhanced by using a coupled-line feed structure for the I/O couplings and cross coupling between the I/O ports. The presented triple-mode filter generates three transmission zeros within its nearby passband. Two of transmission zeros are generated by the triple-mode resonator itself, and the other one is generated by small cross-couplings between the I/O ports. Each of the transmission zero generation condition is analyzed by using an equivalent circuit. Design examples are proposed for a 2.4 GHz WLAN, and then,
the measured results are given to validate the theory.

Ⅱ. Analysis of a Triple-mode Filter

A simple three-pole bandpass filter can be implemented by using a single triple-mode resonator [15]. Fig. 1(a) shows the structure of the proposed triple-mode microstrip filter on a substrate with a relative dielectric constant of 3.5 and a thickness of 0.76 mm. Coupled lines are used for the I/O coupling. This filter configuration allows the induction of a small electric coupling between the I/O ports. This cross coupling path permits the generation of one extra transmission zero.

The triple-mode resonator is a short-circuited stub that is inserted into the symmetric plane of an inter-digital capacitor of a previously studied dual-mode resonator [8]. An extra resonance mode is induced in even-mode by this inserted short-circuited stub. Therefore, the proposed triple-mode resonator supports three modes. Fig. 1(b) shows the equivalent circuit of the proposed triple-mode filter, where $L_1$ and $C_1$ are the inductance and capacitance of the half-wave SIR, $C_M$ is the series capacitance of the inter-digital capacitor, $C_2$ is the parallel capacitance of the inter-digital capacitor, $L_M$ and $L_{M2}$ are the inductance of the short-circuited stub, and $C_{io}$ is the cross coupling capacitor. The proposed triple-mode filter is a symmetric circuit and each of the resonance modes can be calculated with an even-odd mode analysis.

Fig. 2 shows the equivalent circuit of each odd and even mode without a cross coupling capacitor. In an odd mode, a virtual ground exists in the symmetric plane of the triple-mode resonator. The $f_{\text{odd}}$ is induced, which is the fundamental resonant frequency of the proposed triple-mode resonator. The $f_{\text{odd}}$ is also calculated as follows:

$$f_{\text{odd}} = \frac{1}{2\pi \sqrt{L_1(C_1+C_M+C_{io})}} \tag{1}$$

In an even mode, the virtual ground is replaced by a virtual open circuit. The $f_{\text{even}1}$ and $f_{\text{even}2}$ are induced. The $f_{\text{even}1}$ and $f_{\text{even}2}$ are also calculated as follows:

$$f_{\text{even}1} = \frac{1}{2\pi} \sqrt{\frac{b+\sqrt{b^2-4ac}}{2a}} \tag{2a}$$

$$f_{\text{even}2} = \frac{1}{2\pi} \sqrt{\frac{b-\sqrt{b^2-4ac}}{2a}} \tag{2b}$$

where

$$\begin{align*}
    a &= L_{M2}(L_1+2L_{M2})(C_1+C_{io})(2C_M+C_2) + C_2C_{M2} \\
    b &= -(C_1+C_M+C_{io})(L_1+2L_{M2}) \\
    c &= (C_1+C_{io})(2C_M+C_2)
\end{align*}$$

and $c=1$.

Fig. 3 shows the simulated responses of Fig. 1(b) versus various $L_M$ and $L_{M2}$ values with small I/O coupling and zero $C_{io}$. The 0.05 pF lumped capacitor is used for the I/O coupling. Fig. 3(a) shows that the $L_M$ value does not affect the $f_{\text{odd}}$, but it affects $f_{\text{even}1}$ from 2.353 to 2.269 GHz and $f_{\text{even}2}$ from 2.613 to 2.569 GHz when the $L_M$ value increases from 0 to 0.4 nH and $L_{M2}$ is 12.6 nH. Two transmission zeros are also generated in the stopband. One transmission zero is located near the passband and the other one is located in an upper stopband. These generations of transmission zeros result from influences of self cross couplings. The inserted capacitance can be considered as an electric coupling (E) and the applied short-circuited shunt stub can be considered as a magnetic coupling (M). If $L_{M2}=0$, then the transmission zeros are not generated. The second trans-
mission zero is also heavily shifted downwards when the value of $L_M$ increases.

Similarly, Fig. 3(b) shows that $L_{M2}$ does not affect the $f_{odd}$ value, but it does affect $f_{even1}$ from 2.321 to 2.275 GHz and $f_{even2}$ from 2.844 to 2.488 GHz when the $L_{M2}$ value increases from 10 to 14 nH and $L_M$ is 0.33 nH. The $f_{odd}$ is not affected by $L_M$ and $L_{M2}$ but $f_{even1}$ and $f_{even2}$ are mainly affected by each $L_M$ and $L_{M2}$. In short, the resonant frequencies of the proposed triple-mode can be determined to satisfy the filter specification when $f_{odd}$ is tuned first and then, $f_{even1}$ and $f_{even2}$ are tuned by using $L_M$ and $L_{M2}$.

The filter design procedure is based on tuning the resonant frequencies of the triple-mode resonator, i.e., $f_{odd}$, $f_{even1}$ and $f_{even2}$, which can be tuned to satisfy the filter specification. The external quality factor can be tuned by using widths and space of the coupled-line [16].

In this paper, the transmission pole frequencies of 3rd-order Chebyshev bandpass filter are used for filter design. The filter specifications are: the center frequency is 2.45 GHz and the fractional bandwidth is 300 MHz.
Table 1. Comparison of previously reported results

<table>
<thead>
<tr>
<th>Ref.</th>
<th>$f_c$ (GHz)/FBW(%)</th>
<th>Insertion loss (dB)</th>
<th>$h$ (mm), $\varepsilon_r$</th>
<th>Size (mm×mm)</th>
<th>Electrical size ($\lambda_g \times \lambda_g$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. [9]</td>
<td>2.35 / 14.9</td>
<td>1.15</td>
<td>N/A, 2.625</td>
<td>25×15</td>
<td>N/A</td>
</tr>
<tr>
<td>Ref. [10]</td>
<td>2 / 30.69</td>
<td>1.13</td>
<td>1, 9.2</td>
<td>21.7×21.7</td>
<td>0.36×0.36</td>
</tr>
<tr>
<td>Ref. [11]</td>
<td>2.5 / 8</td>
<td>1.7</td>
<td>1.524, 3.66</td>
<td>36.9×16.05</td>
<td>0.522×0.227</td>
</tr>
<tr>
<td>Ref. [12]</td>
<td>3.4 / 15</td>
<td>1</td>
<td>0.8, 2.55</td>
<td>15.2×15.8</td>
<td>0.251×0.261</td>
</tr>
<tr>
<td>Ref. [13]</td>
<td>5.06 / 4.3</td>
<td>2.2</td>
<td>0.831, 3.38</td>
<td>10.9×10.9</td>
<td>0.302×0.302</td>
</tr>
<tr>
<td>Ref. [14]</td>
<td>2.4 / 15.8</td>
<td>0.78</td>
<td>0.508, 2.625</td>
<td>N/A</td>
<td>0.23×0.17</td>
</tr>
<tr>
<td>Ref. [15]</td>
<td>2.45 / 20</td>
<td>1</td>
<td>0.75, 3.5</td>
<td>8.3×4.7</td>
<td>0.11×0.063</td>
</tr>
<tr>
<td>This work</td>
<td>2.45 / 10.6</td>
<td>1.68</td>
<td>0.75, 3.5</td>
<td>7.9×7.2</td>
<td>0.107×0.098</td>
</tr>
</tbody>
</table>

$f_c$: center frequency of filter, $\varepsilon_r$: relative permittivity of substrate, $h$: thickness of substrate, $\lambda_g$: guided wavelength.

The coefficients of the 3rd-order Chebyshev filter are: $g_0=g_4=1$, $g_1=g_3=0.8794$, and $g_2=1.1132$ with a 0.05 dB equal ripple level. The transmission pole frequencies are: 2.3 GHz, 2.44 GHz, and 2.58 GHz.

Fig. 4 shows the frequency response of the designed triple-mode filter versus $C_o$. The element values of the equivalent circuit are: $L_1=8$ nH, $C_{10}=0.29$ pF, $C_1=0.56$ pF, $C_2=0.24$ pF, $C_M=0.033$ pF, $L_M=0.4$ nH, and $L_{2M}=13.1$ nH. Using a small $C_o$, the extra transmission zero is generated within a lower passband and the position of a second transmission zero can be controlled. A small value of $C_o$ must also be chosen to enhance the skirt characteristics of a filter. In the case of $C_o=0.03$ pF, only one transmission zero exists. The transmission characteristics of the filter can be calculated from the odd and even mode input admittances [16]. The transmission zero condition is $Y_O-Y_E=2C_o$. Fig. 5 shows the admittance graph of $Y_O-Y_E$ and $2C_o$ versus $C_o$. In the case of $C_o\leq0.02$ pF, three intersection points exist but in the case of $C_o>0.03$ pF, only one intersection point exists. The position of a second transmission zero can also be...
easily controlled by using a small $C_{io}$.

Fig. 6 shows the frequency response of a designed triple-mode filter with 0.01 pF of $C_{io}$, and it shows good skirt characteristics.

III. Experimental Results

Fig. 7 shows the layout of the fabricated triple-mode filter. The short-circuited stubs use 0.3 mm vias. The size of the single resonator is only 7.9 mm $\times$ 7.2 mm. A comparison of the various published triple-mode resonators with the proposed resonator is shown in Table 1. The electrical sizes of the resonators are calculated at each central frequency in order to compare the area miniaturization of the resonators, irrespective of the various substrates and center frequencies. The fabricated filter is measured on an Anritsu 37325A network analyzer, with the measured and simulation performance as shown in Fig. 8. Measured results show that the passband, which is centered at 2.45 GHz, has an insertion loss of <1.68 dB. The wide response of the proposed filter is plotted with previous work [15] in Fig. 8(c). Three transmission zeros are positioned nearby passbands at 1.32 GHz, 2.73 GHz, and 3.3 GHz, respectively. Compared to [15], the skirt characteristics are much enhanced and some first harmonic frequency occurred at 9.78 GHz. However, it also shows a wide stopband, with rejection level of 19 dB up to 13.5 GHz.

IV. Conclusion

A compact triple-mode filter with enhanced skirt characteristics was proposed. The skirt characteristics were enhanced using a small cross coupling between the I/O ports. The triple bandpass filter of size 0.107 $\lambda$ $\times$ 0.098 $\lambda$ was designed and fabricated for a 2.4 GHz WLAN application. It has three transmission zeros within its nearby passband and it also shows good harmonic characteristics.

References

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