Design of Lowpass Filter and Lowpass-Highpass Diplexer with LTCC Technology

Chunxia Zhou 1*, Yongxin Guo 2, and Wen Wu 1

1 Ministerial Key Laboratory of JGMT
Nanjing University of Science and Technology, Nanjing, 210094, China
zhouchx1010@gmail.com*, wuwen@njust.edu.cn
2 Department of Electrical and Computer Engineering
National University of Singapore, Singapore 117583, Singapore
yongxin.guo@nus.edu.sg

Abstract — A compact lowpass filter (LPF) and a lowpass-highpass diplexer (LHD) with both sharp roll-off and wide stopband is presented in this paper. The proposed LPF is realized by cascading modified hairpin unit consisting of one U-shape stripline and one pair of offset-coupled striplines with multilayer low-temperature cofired ceramic (LTCC) technology. The LHD is realized by shunting a lowpass filter and a highpass filter at a common junction to achieve all-reject in one port. Good agreement can be achieved by the simulated and measured results.

Index Terms — Coupled lines, Low-Temperature Co-fired Ceramic (LTCC), Lowpass filter (LPF), Lowpass-Highpass Diplexer (LHD).

I. INTRODUCTION

Compact, low cost, and highly integrated passive and active components are highly demanded by wireless-device manufacturers. The low temperature cofired ceramic (LTCC) technology, as one of the most promising methods, has been extensively utilized in recent years. LTCC offers layout flexibility and three-dimensional (3D) integration capability to produce embedded passive components, for example, filters [1, 2] and antennas [3], phase shift [4] and coupler [5]. The lowpass filter (LPF) is one of key passive components that are widely used in wireless systems to filter out unwanted signals. There are several conventional methods to design LPFs such as using shunt stubs, high-low impedance transmission lines, or cascading multiple resonators [6, 7]. However, it is quite hard to achieve LPFs with sharp attenuation skirt and compact size simultaneously. To overcome this difficulty, modified hairpin resonators have been widely adopted due to its compactness and flexibility. Various types of miniaturized and performance-improved LPFs have been studied based on hairpin resonators [8-14]. Elliptic-function LPFs with a wide stopband are presented in [8] by cascading microstrip stepped-impedance hairpin resonators. In [9], stopband-extended LPFs were realized by centrally tap-connecting the microstrip coupled-line hairpin resonator. In [10], a LPF with wide stopband was designed by cascading microstrip coupled-line hairpin resonator, semi-circle defected ground structures and semi-circle stepped-impedance shunt stubs. Stepped-impedance hairpin resonators with an interdigital structure [11, 12], shunt open-stubs [13], and radial stubs [14] were used for designing LPFs with sharp and expanded stopband.

In this paper, a compact LTCC LPF with sharp roll-off and wide stop-band is presented by cascading modified hairpin units. The unit consists of one U-shape stripline and one pair of offset-coupled striplines with multilayer LTCC technology. Measured results indicate that the designed filter has an ultra-wide stopband rejection better than 10 dB up to 20 GHz and a sharp roll-off of 81 dB/GHz. Furthermore, a lowpass-highpass diplexer (LHD) is presented to achieve all-reject in one port. It is realized by shunting a lowpass filter and a highpass filter at a common junction.

II. LOWPASS FILTER DESIGN

Figure 1(a) shows the circuit schematic of the lowpass filter. It is realized by four sections of modified hairpin units. Each unit consists of one U-shape stripline and one pair of offset-coupled striplines with multilayer LTCC technology. Measured results indicate that the designed filter has an ultra-wide stopband rejection better than 10 dB up to 20 GHz and a sharp roll-off of 81 dB/GHz. Furthermore, a lowpass-highpass diplexer (LHD) is presented to achieve all-reject in one port. It is realized by shunting a lowpass filter and a highpass filter at a common junction.
values of the 9-order elliptic-function LPF can be calculated as follows: \( L_1 = 2.611 \text{ (nH)}, \ L_2 = 1.812 \text{ (nH)}, \ L_3 = 1.499 \text{ (nH)}, \ L_4 = 1.878 \text{ (nH)}, \ C_{\text{g1}} = 0.097 \text{ (PF)}, \ C_{\text{g2}} = 0.584 \text{ (PF)}, \ C_{\text{g3}} = 0.803 \text{ (PF)}, \ C_{\text{g4}} = 0.385 \text{ (PF)}, \ C_{\text{p1}} = 0.686 \text{ (PF)}, \ C_{\text{p2}} = 0.415 \text{ (PF)}, \ C_{\text{p3}} = 0.399 \text{ (PF)} \) and \( C_{\text{p4}} = 0.497 \text{ (PF)} \). Then, the relationship between the parameters in Fig. 1 (a) and those in Fig. 1 (b) can be obtained [8]:

\[
L_i = Z_i \sin(\theta_i) / \omega \quad (H), \quad (1)
\]

\[
C_g = (Z_{g_i} - Z_{m}) / (2\omega Z_{m} \cos(\theta_i)) \quad (F), \quad (2)
\]

\[
C_m = 1 / (\omega Z_{m} \cos(\theta_i)) \quad (F), \quad (3)
\]

\( i = 1, 2, 3, 4 \).

By comparing Equations (2) and (3), we can get:

\[
Z_{g_i} / Z_m = (2C_g + C_m) / C_m. \quad (4)
\]

Fig. 1. Diagram of proposed LPF. (a) Circuit schematic and (b) corresponding equivalent circuit.

### III. LOWPASS-HIGHPASS DIPLEXER DESIGN

Figure 2 shows the circuit schematic of the proposed LHD. It is realized by shunting a lowpass filter and a highpass filter at a common junction. It consists of five striplines with electric length of \( \theta_i \) and impedance of \( Z_i \) \( i = 1, 2, 3, 4, 7 \), and four coupled lines with electric length of \( \theta_i \) and even- and odd-mode impedance of \( Z_{e_i} \) and \( Z_{o_i} \) \( i = 5, 6, 8, 9 \). To minimize reflections at the input port 1, the complex input admittances \( Y_{\text{in,LP}} \) and \( Y_{\text{in,HP}} \) of the two filters should satisfy at all frequencies the equation:

\[
Y_{\text{in}} = Y_{\text{in,LP}} + Y_{\text{in,HP}} = Y_0. \quad (5)
\]

This condition can be split into the following two conditions:

\[
\text{Re}(Y_{\text{in,LP}}) + \text{Re}(Y_{\text{in,HP}}) = Y_0, \quad (6)
\]

\[
\text{Im}(Y_{\text{in,LP}}) + \text{Im}(Y_{\text{in,HP}}) = 0. \quad (6)
\]

Fig. 2. Circuit schematic of the proposed LHD.

### IV. FILTER AND DIPLEXER IMPLEMENTATION IN LTCC TECHNOLOGY

The filter and diplexer are designed in a 10-layer LTCC substrate, with the relative permittivity of 5.9, loss tangent of \( \tan\delta = 0.0015 \), and thickness of each substrate layer of 96 \( \mu \text{m} \). There are 11 metal layers from top to bottom. The 3D configuration of the proposed LPF is illustrated in Fig. 3. The configuration is build-up according to the basic circuit shown in Fig. 1 (a). The sections of four transmission lines are realized by U-shape striplines in metal layer 5, layer 6 and layer 8, with width of 0.2 mm. According to Equation (1), we can get \( \theta_1 = 90^\circ, \theta_2 = 49.40^\circ, \theta_3 = 38.90^\circ \) and \( \theta_4 = 51.90^\circ \). The sections of four pairs of coupled lines are realized by offset-coupled striplines with width of 0.53 mm. Then adjusting the relatively positions of the offset-coupled striplines to satisfying Equation (4), we can get each \( Z_{e_i}, Z_{o_i}, \) and \( \theta_i \) \( i = 1, 2, 3, 4 \). With trial-and-error operations, the first pair of coupled lines is determined in layers 2 and 8, the second in layers 7 and 8, the third in layers 6 and 7 and the forth in layers 4 and 6. Furthermore, \( Z_{e_1} = 28.2 \Omega, \ Z_{o_1} = 22.1 \Omega, \ \theta_{c_1} = 25.8^\circ, \ Z_{e_2} = 50.6 \Omega, \ Z_{o_2} = 13.2 \Omega, \ \theta_{c_2} = 27.6^\circ, \ Z_{e_3} = 55 \Omega, \ Z_{o_3} = 10.9 \Omega, \ \theta_{c_3} = 28.7^\circ, \ Z_{e_4} = 48 \Omega, \ Z_{o_4} = 18.1 \Omega, \ \theta_{c_4} = 29.6^\circ \). After optimization using Ansoft HFSS, we can get that the lengths of the four striplines corresponding to \( \theta_1, \theta_2, \theta_3 \) and \( \theta_4 \) are 5.45 mm, 4.36 mm, 3.13 mm and 5.2 mm respectively. The lengths of the coupled striplines corresponding to \( \theta_{c_1}, \theta_{c_2}, \theta_{c_3} \) and \( \theta_{c_4} \) are 1.8 mm, 2 mm, 2.2 mm and 2.24 mm respectively. The designed parameters of the LPF are summarized in Table 1. The S-parameters in both the simulated and the measured results are shown in Fig. 4. The photo of the filter prototype is shown in Fig. 5. Its overall size is only
4.54×3.37×0.96 mm³. For comparison, Table 2 summarizes the performances of some published lowpass filters. As can be seen from the table, our proposed filter has the properties of sharp roll-off, ultra-wide stopband, and compact size simultaneously.

Table 1: The designed parameters of the LPF

<table>
<thead>
<tr>
<th>i</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>θLi</td>
<td>90°</td>
<td>49.4°</td>
<td>38.9°</td>
<td>51.9°</td>
</tr>
<tr>
<td>Cθi</td>
<td>25.8°</td>
<td>27.6°</td>
<td>28.7°</td>
<td>29.6°</td>
</tr>
<tr>
<td>Zel (Ω)</td>
<td>28.2</td>
<td>50.6</td>
<td>55</td>
<td>48</td>
</tr>
<tr>
<td>Zoi (Ω)</td>
<td>22.1</td>
<td>13.2</td>
<td>10.9</td>
<td>18.1</td>
</tr>
<tr>
<td>LLI (mm)</td>
<td>5.45</td>
<td>4.36</td>
<td>3.13</td>
<td>5.2</td>
</tr>
<tr>
<td>LCi (mm)</td>
<td>1.8</td>
<td>2</td>
<td>2.2</td>
<td>2.24</td>
</tr>
</tbody>
</table>

Fig. 3. 3D configuration of the proposed LPF.

Fig. 4. Simulated and measured results of the LPF.

Table 2: Performance comparisons among published filters and the proposed one

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Roll Off (dB/GHz)</th>
<th>Stopband Up to (GHz)</th>
<th>Circuit Size (λg<em>λg</em>)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[8]</td>
<td>37</td>
<td>4.8</td>
<td>0.09*0.35</td>
</tr>
<tr>
<td>[9]</td>
<td>45</td>
<td>15</td>
<td>0.23*0.27</td>
</tr>
<tr>
<td>[10]</td>
<td>74</td>
<td>6</td>
<td>0.11*0.10</td>
</tr>
<tr>
<td>[11]</td>
<td>95</td>
<td>9</td>
<td>0.10*0.21</td>
</tr>
<tr>
<td>[12]</td>
<td>28</td>
<td>12</td>
<td>0.08*0.08</td>
</tr>
<tr>
<td>[13]</td>
<td>43.2</td>
<td>12</td>
<td>0.39*0.83</td>
</tr>
<tr>
<td>This work</td>
<td>81</td>
<td>20</td>
<td>0.14*0.11</td>
</tr>
</tbody>
</table>

The 3D configuration of the proposed LHD is illustrated in Fig. 6. The configuration is built up according to the basic circuit shown in Fig. 2. The sections of five transmission lines are realized by microstrip line in the top metal (θ1) with width of 0.2 mm, U-shape striplines in metal layer 6 (θ2) and layer 4 (θ4) with width of 0.2 mm, stripline in layer 4 (θ4) with width of 0.6 mm and L-shape stripline in metal layer 6 (θ8) with width of 0.2 mm. The sections of four pairs of coupled lines are realized by offset-coupled striplines in layers 4 and 7 (θ5) with width of 0.6 mm, the second in layers 2 and 7 (θ6) with width of 0.6 mm, the third in layers 5 and 6 (θ8) with width of 0.2 mm and the forth in layers 4 and 6 (θ9) with width of 0.6 mm. To satisfy Equation (5), the design parameters are determined as follows: θ1=43°, θ2=47°, θ4=46°, θ5=29°, θ6=37°, θ8=20°, θ9=47°, θ10=25° and θ11=10°.

After optimization using Ansoft HFSS, we can get that the lengths of one microstrip line and four striplines corresponding to θ1, θ2, θ4, θ5 and θ6 are 3.3 mm, 3.6 mm, 3.5 mm, 2.2 mm and 1.6 mm respectively. The lengths of the coupled striplines corresponding to θ5, θ6, θ8 and θ9 are 2.7 mm, 1.5 mm, 1.9 mm and 0.5 mm respectively. The designed parameters of the LHD are summarized in Table 3. Both the simulated and the measured results are shown in Fig. 7. The photo of the diplexer prototype is shown in Fig. 8. Its overall size is only 5.8×5.3×0.96 mm³. For comparison, Table 4 summarizes the performances of some published diplexers.
Fig. 6. 3D configuration of the proposed LHD.

Table 3: The designed parameters of the LHD

<table>
<thead>
<tr>
<th>i</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_i$</td>
<td>43$^\circ$</td>
<td>47$^\circ$</td>
<td>46$^\circ$</td>
<td>29$^\circ$</td>
<td>37$^\circ$</td>
<td>20$^\circ$</td>
<td>47$^\circ$</td>
<td>25$^\circ$</td>
<td>10$^\circ$</td>
</tr>
<tr>
<td>$L_i$ (mm)</td>
<td>3.3</td>
<td>3.6</td>
<td>3.5</td>
<td>2.2</td>
<td>2.7</td>
<td>1.5</td>
<td>1.6</td>
<td>1.9</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 4: Performance of diplexers

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Type</th>
<th>$f_c$ (GHz)</th>
<th>Size ($\lambda_g*\lambda_g$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>[15]</td>
<td>Lowpass-Bandpass</td>
<td>1.5</td>
<td>0.80*0.41</td>
</tr>
<tr>
<td>[16]</td>
<td>Lowpass-Highpass</td>
<td>0.92</td>
<td>0.43*0.20</td>
</tr>
<tr>
<td>This work</td>
<td>Lowpass-Highpass</td>
<td>4.5</td>
<td>0.18*0.16</td>
</tr>
</tbody>
</table>

V. CONCLUSION

A compact LPF and LHD with sharp roll-off skirt and wide stopband are implemented in multilayer LTCC. The LPF is realized by cascading modified hairpin unit consisting of one U-shape stripline and one pair of offset-coupled striplines. The designed filter has an ultra-wide stopband rejection better than 10 dB up to 20 GHz and a sharp roll off of 81 dB/GHz. Furthermore, the size of the filter is only 4.54×3.37 mm². The LPD is realized by shunting a lowpass filter and a highpass filter at a common junction to achieve all-reject in one port. The size of the diplexer is 4.54×3.37 mm². The measured results are in good agreements with the simulation predictions.

ACKNOWLEDGEMENT

This work was supported by the National Natural Science Foundation Committee of China (61401202).

REFERENCES


for IEEE Antennas and Wireless Propagation Letters (AWPL). He was a recipient of the Young Investigator Award 2009, National University of Singapore and the 2013 “Raj Mittra” Travel Grant Senior Researcher Award.

Wen Wu (SM’10) received the Ph.D. degree in Electromagnetic Field and Microwave Technology from Southeast University, Nanjing, China, in 1997.

He is currently a Professor with the School of Electronic Engineering and Optoelectronic Technology and an Associate Director with the Ministerial Key Laboratory of JGMT, Nanjing University of Science and Technology, Nanjing, China. He has authored and co-authored over 120 journal and conference papers. He has submitted five patent applications. His current research interests include microwave and millimeter-wave (mm-wave) theories and technologies, microwave and mm-wave detection, and multimode compound detection.

Wu was a six-time recipient of the Ministerial and Provincial-Level Science and Technology Award.