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Synthesis of Wideband Parallel-Coupled Line Bandpass Filters With Non-Equiripple Responses
Shan Shan Gao and Sheng Sun, Senior Member, IEEE

Abstract—This letter proposes a synthesis of wideband parallel-coupled line bandpass filters with controllable non-equiripple frequency responses. Different from the traditional Chebyshev transfer function filters, the reflection lobes of the proposed non-equiripple filters can be redistributed within the operating passband. As a result, the proposed filters have a reduced sensitivity to manufacturing errors and exhibit good tolerance control for maximum in-band reflection loss. By deriving the transfer functions, a synthesis approach with a set of nonlinear equations can be established according to the specifications such as the bandwidth and predetermined reflection lobes. Without performing any post optimization in the full-wave simulation, the non-equiripple synthesized results have less sensitivity in comparison with those obtained from traditional Chebyshev transfer functions with equiripple frequency responses.

Index Terms—Bandpass filter (BPF), non-equiripple responses, parallel-coupled line, synthesis design, wideband.

I. INTRODUCTION

W
ith the rapid development of industrial electronics and manufacturing technology, the requirements for high-performance passive RF/microwave circuits increase significantly. In the past years, most of the wideband bandpass filters (BPFs) are Chebyshev transfer function filters, which exhibit the equiripple in-band and the maximally flat out-of-band frequency responses [1]. However, the sensitivity of manufacturing errors will introduce some discrepancies, and the insufficient unloaded-Q factors also make the insertion losses of BPFs worse, especially for the frequency region near the transition from passband to stopband [2]. A possible solution to solve this problem is to employ the Chained function as transfer function or targeted insertion loss function [3], [4]. However, its in-band reflection levels are adjusted by selecting different seed functions, and the individual reflection lobes cannot be arbitrarily controlled once the seed functions are determined. On the other hand, the Chained function filters were initially proposed to improve the design for narrow-band high-order Chebyshev filters, and the resultant reflection zeros in the passband are usually very close to each other or overlapped. To circumvent this problem, a dome-shaped envelope filtering function was proposed to provide better selectivity and in-band flatness, in comparison with the Chain function filters, by redistributing the positions of reflection zeros [5].

Very recently, an UWB filter with non-equiripple response and good in-band flatness was presented and implemented in [6]. Due to the T-junction influence, the filters need further optimization to obtain the required responses. Instead of using shunt short-circuited stubs, BPF with parallel-coupled line is usually more sensitive in fabrication because of the tight coupled-line sections. In this letter, a detailed derivation of the modified synthesis will be first provided in order to obtain controllable non-equiripple responses for parallel-coupled line BPFs. Based on the expanded characteristic function \( F \) [7], a new characteristic function with a series of unknown coefficients can be constructed for the non-equiripple responses. For the traditional cases with equiripple responses, these coefficients of the expanded characteristic function can be mathematically derived [7]. In order to obtain the non-equiripple responses, the in-band reflection lobes \( RL_{in} \) of a traditional Chebyshev function have to be redistributed, which can be realized by finding a new set of coefficients. According to the specified bandwidth and reflection lobes, a system of nonlinear equations can be established, where the unknown coefficients can be determined by using Gauss-Newton iterations. Finally, non-equiripple function filter with four in-band reflection zeros is implemented and verified experimentally.

II. SYNTHESIS OF FILTERS WITH NON-EQUIRIPPLE RESPONSES

A wideband parallel-coupled line BPF with a single multi-mode resonator (MMR) is shown in Fig. 1(a). It consists of two parallel-coupled line sections with even- and odd-mode characteristic impedances \( Z_{0e} \) and \( Z_{0o} \), which are connected by an \( m \)-section non-uniform transmission line with the characteristic impedances \( Z_{1\sim m} \). The electrical lengths of all the involved line sections are chosen with \( \theta_e \) at the lower cutoff frequency. Fig. 1(b) illustrates its exact equivalent transmission line network with the normalized impedances \( z_{a}, z_{b}, \) and \( z_{1\sim m} \). By multiplying the individual \( ABCD \) matrices of each line section, the return loss function of entire network can be analytically derived from the overall \( ABCD \) matrix as

\[
|S_{11}| = \frac{|F|^2}{1 + |F|^2} \quad (1a)
\]

and

\[
F = \frac{B - C}{2} \quad (1b)
\]
Fig. 1. Parallel-coupled line BPF. (a) Layout. (b) Equivalent transmission line network.

is defined as a characteristic function. Following the direct synthesis approach in [7], it is easy to observe that function \( F \) can be expressed as:

\[
F = j \left( k_1 \frac{\cos^2 \theta}{\sin \theta} + k_2 \frac{\cos^2 \theta}{\sin \theta} + k_3 \frac{1}{\sin \theta} \right) \tag{2}
\]

for four in-band reflection zeros. It implies that the function \( F \) in (2) can also be employed to construct the non-equiripple responses by tuning these coefficients. As shown in Fig. 2, the non-equiripple responses with four in-band reflection zeros can be easily achieved by choosing the proper coefficients. In this case, \( \theta_{RL1} = 90^\circ \). Substituting \( \theta_{RL3} = 90^\circ \) into (2) gives \( k_3 = F_1 \). In order to determine the coefficients \((k_1, k_2, \text{and } k_3)\) numerically, three equations should satisfy the boundary condition according to the filter specifications, i.e., \( \theta_{RL1}, \text{RL}_1, \text{and } \text{RL}_2 \). According to the pre-specified \( \theta_{RL1}, \text{RL}_1, \text{and } \text{RL}_2 \), we have

\[
\begin{align*}
&\begin{cases}
  k_1 \frac{\cos^4 \theta_{RL1}}{\sin \theta_{RL1}} + k_2 \frac{\cos^4 \theta_{RL1}}{\sin \theta_{RL1}} + F_1 \frac{1}{\sin \theta_{RL1}} - F_1 = 0 \\
  k_1 \frac{\cos^4 \theta_{RL1}}{\sin \theta_{RL1}} + k_2 \frac{\cos^4 \theta_{RL1}}{\sin \theta_{RL1}} + F_1 \frac{1}{\sin \theta_{RL1}} - F_2 = 0 \\
  k_1 (3 \cos^3 \theta_{RL1} - 4 \cos \theta_{RL1}) + k_2 (\cos^3 \theta_{RL1} - 2 \cos \theta_{RL1}) - k_3 \cos \theta_{RL1} = 0
\end{cases}
\end{align*}
\tag{3}
\]

where \( F_{1,2} \) is the value of \( F \) corresponding to \( \text{RL}_{1,2} \). From (3), the unknown coefficients \((k_1, k_2, \text{and } \theta_{RL2})\) can be solved numerically by using Gauss-Newton iterations. The starting values of these coefficients can be obtained from traditional Chebyshev function filter by direct mathematical derivation from the characteristic function \( F \) [7]. Meanwhile, the characteristic impedances of filter topology in Fig. 1(b) can be explicitly determined, where \( m \) is set to 1 for the topology with four in-band reflection zeros.

III. Sensitivity Analysis

Due to the effects of the inherent loss and dispersion of the transmission lines, the unloaded-Q will become an insufficient value within the passband, which usually makes the insertion loss worse. These properties may result in the overlapping of reflection zeros and the bandwidth decrement. The proposed non-equiripple filters with dome-shaped envelope of the \( |S_{11}| \) in-band response can be used to compensate this influence. Fig. 3 shows the desired and EM simulated in-band frequency responses for the case with four reflection zeros. It can be found that the transmission coefficient of the proposed non-equiripple filter is better than the traditional Chebyshev function filter. Furthermore, the bandwidth decrement of the proposed non-equiripple filter is less than that of the traditional one. It can be seen that the maximum value of \( |S_{11}| \) within the passband is \(-12.43\) dB in the traditional Chebyshev function filter, which cannot satisfy the required \(-15\) dB. However, the maximum \( |S_{11}| \) values of the non-equiripple filters with \( \text{RL}_2 \) set to \( 20 \) dB is \(-16.47\) dB within the passband.

Fig. 3. S-magnitudes of the traditional Chebyshev function (dot-line) and the proposed non-equiripple filters (dash- and dot-dashed lines) (\( \text{RL}_1 = 15 \) dB and \( \theta_{RL1} = 63^\circ \)).

Fig. 4. Nominal dimensions, \(-1 \) mil, \(+1 \) mil frequency responses with four in-band reflection zeros \((\text{RL}_1 = 15 \) dB, \( \theta_{RL1} = 63^\circ \)). (a) Traditional Chebyshev function filters. (b) The proposed non-equiripple filters \((\text{RL}_2 = 20 \) dB).

TABLE I

<table>
<thead>
<tr>
<th>Type</th>
<th>( \text{RL}_1 ) (dB)</th>
<th>( \text{RL}_2 ) (dB)</th>
<th>Oversize</th>
<th>( S_{11_{max}} ) (dB)</th>
<th>( \Delta_{RL1} ) (dB)</th>
<th>Error (( \Delta ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>15</td>
<td>15</td>
<td>\pm 0 mil</td>
<td>-12.42</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Worst</td>
<td>15</td>
<td>15</td>
<td>-1 mil</td>
<td>-10.81</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Best</td>
<td>15</td>
<td>15</td>
<td>+1 mil</td>
<td>-15.0</td>
<td>63%</td>
<td>( \uparrow )5%</td>
</tr>
</tbody>
</table>

TABLE II

<table>
<thead>
<tr>
<th>Type</th>
<th>( \text{RL}_1 ) (dB)</th>
<th>( \text{RL}_2 ) (dB)</th>
<th>Oversize</th>
<th>( S_{11_{max}} ) (dB)</th>
<th>( \Delta_{RL1} ) (dB)</th>
<th>Error (( \Delta ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>15</td>
<td>20</td>
<td>\pm 0 mil</td>
<td>-14.67</td>
<td>57.3%</td>
<td>( \downarrow )4.5%</td>
</tr>
<tr>
<td>Worst</td>
<td>15</td>
<td>20</td>
<td>-1 mil</td>
<td>-13.66</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Best</td>
<td>15</td>
<td>20</td>
<td>+1 mil</td>
<td>-17.88</td>
<td>62.2%</td>
<td>( \uparrow )3.7%</td>
</tr>
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</table>
non-equiripple filters have a reduced sensitivity to manufacturing errors and exhibit good tolerance control for maximum in-band return loss. It can also be considered as a pre-distortion technique for the traditional parallel-coupled line structure.

IV. SIMULATED AND MEASURED RESULTS

To verify our proposed wideband non-equiripple BPF, the filter with fractional bandwidth $\Delta = 60\%$ ($RL_1 = 15\, \text{dB}$, $RL_2 = 20\, \text{dB}$) is designed on the substrate with the thickness of 0.8 mm and dielectric constant of 4.8. The layout of the proposed non-equiripple filter is shown in Fig. 5. Fig. 6 shows synthesized, simulated, and measured frequency responses and group delay of the designed non-equiripple BPF. The layout dimensions for full-wave simulated results are obtained based on synthesized impedances without implementing any post-optimization. It can be noticed that the 15 dB reflection bandwidth of 2.13 to 3.84 GHz and 2.12 to 3.9 GHz are observed in the simulated and measured results for the filters. The corresponding fractional bandwidth of the simulation and measurement are 57.3% and 59.1%, respectively. And the maximum return losses of the simulated and measured results are 16.47 dB and 15.35 dB, respectively. On the other hand, both of the simulated and measured maximum variations are less than 0.4 ns within the passband. In addition, the traditional equiripple filters with $\Delta = 60\%$ ($RL_1 = RL_2 = 15\, \text{dB}$) synthesized by the method in [7] are also designed for comparison. As shown in Fig. 7, the maximum return losses of the simulated and measured results of traditional equiripple filters are 12.42 dB and 10.9 dB, respectively, which cannot satisfy the required 15 dB. Hence, the measured results show that the proposed non-equiripple filters can satisfy the required reflection lobes easily, which are usually more sensitive by using the classical synthesis method.

V. CONCLUSION

In this letter, a synthesis approach for non-equiripple wideband BPFs has been systematically presented. The proposed filters with 60% designed bandwidth have been fabricated and validated experimentally. By redistributing $RL_s$ of the traditional Chebyshev function filters, the tolerance to manufacturing errors of ±1 mil can be improved by 2.85 ~ 4.05 dB for the maximum in-band return loss.

REFERENCES