Synthesis of Extracted Pole Filters without the Extra Spikes

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Abstract—This paper proposes a novel synthesis procedure for unified extracted pole filters to remove extra spikes in the stopband. The ideal phase shifters in the prototype circuit can be absorbed into the resonators in the proposed circuit configuration. The synthesis approach is illustrated using a three-pole filter with one transmission zero and verified using a 11-pole filter with 2 transmission zeros. The simulated results verified the validity of the new synthesis method.

Keywords—extracted pole synthesis, spike-free filter.

I. INTRODUCTION

Microwave filter synthesis with extracted pole techniques can realize transmission zeros (Tz) without cross couplings [1]. It is attractive when the specification has extra restriction on the mechanical layout of the filter [2], [3]. Recently, [4] proposed to derive the prototype of a filter network that has dangling resonators with unified extracted pole technique, which covered both extracted pole and non-resonating node (NRN). However, all the existing extracted pole prototypes or NRN circuits suffered from the unwanted spike phenomenon [4]-[6], which prevented this useful approach from applying to the broadband applications.

The root cause for the spikes is that each ideal phase shifter in the prototype circuit must be realized with a transmission line (TL) section in the electromagnetic (EM) model. Although the NRN circuits do not need the phase shifters, however, the NRN is usually realized with a resonator with resonance frequency out of the passband. It fills the role of NRN in passband, with the price of unwanted spikes due to fundamental mode resonance outside the passband. The higher order mode spikes around 1.4x center frequency is beyond the scope of this paper.

This work proposes to remove the unwanted spikes in the extracted pole filters. The main idea is to make the ideal phase shifters as parts of the resonators. Conventionally, resonators in the filter networks need to be sandwiched between two or more inverters to ease the frequency mapping and the immittance slope de-normalization. However, to accommodate the inverter, the phase shifter connecting to the pole producing element (PPE) [1] usually need adding extra 180°.

This work reveals that this requirement is not necessary in the synthesis methods based on proposed extraction method. The elements corresponding to the resonators can be set to the specified values. After the frequency mapping, they are transformed to the half wavelength resonators automatically. As a result, although the inverter before the PPE is removed, the resonators in lowpass prototype can still be mapped to transmission line sections with dispersive effect and unit impedance. Meanwhile, the ideal phase shifter can be set to a relatively small value. Furthermore, they can be absorbed by the adjacent TL sections. Therefore, the spikes caused by the mismatching between the circuit model and the EM model is removed.

This paper analyzes the spike effect using a 3-pole filter with 1 Tz and described the proposed approach to remove the spike. Finally, the proposed theories are verified via an 11-pole filter with a pair of Tz. The simulated response shows that there is no spike in the stopband as expected. Following the results of the new synthesis process, a reduced size wideband filter can be designed analytically with better performance without spikes out of passband.

II. SYNTHESIS OF SPIKE-FREE PROTOTYPE

A. Analysis of Spike Effect

The filter design with extracted pole or NRN technique usually has extra spikes outside the pass band [5], [6]. Those spikes might be acceptable for some narrow band filter applications. However, when the passband is broadened, those spikes will get too close to the passband, which is often unacceptable.

Take a three-degree filter discussed in [4] as an example. It uses the general Chebyshev function which has a normalized Tz at j2.88, the return loss (RL) ripple is set to 22dB. The prototype circuit is shown in Fig. 1 and the values of parameters are listed in Table 1 [4]. All capacitors in the circuit are 1.

Fig. 1. Synthesized lowpass prototype of 3-1 filter.

Table 1. Unified simulation results of 3-1 filter in Fig. 1.

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
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<tbody>
<tr>
<td>J01</td>
<td>1.1378</td>
</tr>
<tr>
<td>b1</td>
<td>0.3411</td>
</tr>
<tr>
<td>J12</td>
<td>0.6202</td>
</tr>
<tr>
<td>θ1</td>
<td>120.1030</td>
</tr>
<tr>
<td>b0</td>
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</tr>
<tr>
<td>θ2</td>
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</tr>
<tr>
<td>b2</td>
<td>120.1030</td>
</tr>
<tr>
<td>J11</td>
<td>0.3411</td>
</tr>
<tr>
<td>J12</td>
<td>1.1378</td>
</tr>
</tbody>
</table>
Using the rectangular waveguide to realize the prototype, the center frequency is 12.5 GHz and the waveguide size is 19.05 mm × 9.525 mm. The distributed equivalent circuit is shown in Fig. 2 and the corresponding element values are listed in Table 2. Note that the resonators of half wavelength correspond to the series inductors [7]. Therefore, extra 90° phase should be added on θ₁ and θ₂. To transform capacitors to half wavelength waveguide TLs, the inverters in Fig. 1 should be re-scaled using (1):

\[ K_{ij} = j \sqrt{\frac{\pi BWF}{2}} \left( \frac{\lambda_{g0}}{\lambda_0} \right) \]

where BWF is the fractional bandwidth, \( \lambda_0 \) and \( \lambda_{g0} \) are the free space wavelength and waveguide wavelength at the resonant frequency of resonator. The capacitor (resonator) must be sandwiched between two inverters. Besides, one must be aware that the physical inverters and the PPE have loading phases. Therefore, \( \theta_{ij} \) and \( \theta_{2p} \) usually is enlarged by an extra 180 degree to cancel out those non-ideal effect.

When the bandwidth is 100 MHz, the response using ideal phase length and TL with waveguide dispersive effect are shown in Fig. 3a and Fig. 3b respectively. In Fig. 3b, two spikes in the stopband induced by \( \theta_1 \) and \( \theta_2 \) can be clearly observed. Here, \( \theta_1 \) and \( \theta_2 \) construct a resonator of which the TE102 mode and TE103 mode are located at 11.42 GHz and 15.07 GHz respectively. The spikes are relatively far from the passband.

However, when the bandwidth is set to 500 MHz shown in Fig. 3c and Fig. 3d, the spikes are located extremely close to passband and cause significant performance degradation. Therefore, traditional extracted pole topology and synthesis process are no longer valid for broadband filters.

### B. Solution to “Spike-free” Unified Extracted Pole Filters

The key to “spike free” is to absorb the ideal phase shifters into the adjacent resonators. Therefore, the inverter between the capacitor and the phase shifter must be removed. Consequently, the de-normalization process in conventional approaches is not applicable. This work proposes to extract the capacitors with the value of the impedance slope of waveguide resonator as:

\[ C_s = \frac{\pi BWF}{2} \left( \frac{\lambda_{g0}}{\lambda_0} \right)^2. \]

In the example of the 500 MHz bandwidth, \( C_s = 0.1042 \). It translates to a half wavelength waveguide section during the
bandpass transformation process directly without scaling the adjacent inverters.

Furthermore, it is worth noting that using waveguide TLs to realize resonators is a narrow band approximation. Therefore, the phase shifters to be absorbed into resonator must be as small as possible. To this end, this work proposed a novel circuit configuration as shown in Fig. 4.

![Fig. 4. Prototype circuit of the 3-1 filter without spikes in the stopband.](image)

Different from the conventional synthesis approach, the combination of $C_{1p}$ and $C_{2p}$ represents only one resonator, i.e., the extraction of those two capacitances only makes the pole of the filter function reduce one. The inserted redundant capacitance can bring more degrees of freedom in synthesis. Since $C_{1p}$ does not make the order of the filter function reduced, the value of $J_{12p}$ can be assigned freely. $J_{12p}$ is adjusted to find the solution with smaller ideal phase shifters. The synthesis results are listed in Table 3.

![Table 3. Elements values of a synthesis solution.](image)

The distributed model of Fig. 4 can be built as Fig. 5. Taking the additional $90^\circ$ phase into consideration, the $\theta_{1p}=1.1681^\circ$ and $\theta_{2p}=-1.3188^\circ$, i.e. very small values.

![Fig. 5. Distributed bandpass model of the 3-1 filter in the Fig. 3.](image)

When the ideal phase lengths $\theta_{1p}$ and $\theta_{2p}$ are replaced with waveguide TLs, the response without any optimization is shown in Fig. 6. Obviously, the spikes caused by dispersive phase shifters in the stopband are eliminated and the performance deterioration is much less serious than that shown in Fig. 3d.

It is worth noting that $b_0p$ in Table 3 is relatively large. That’s because the fractional bandwidth is relatively small, resulting in very small extraction value of capacitance from (2). Therefore, the proposed synthesis procedures are more suitable for broadband filters, such as filters with fractional bandwidth more than 10%.

![Fig. 6. Simulated response of the 3-1 filter in Fig.5 with TL represented phase shifters.](image)

<table>
<thead>
<tr>
<th>Element</th>
<th>Value</th>
<th>Element</th>
<th>Value</th>
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<td>0</td>
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<td>$b_{9}$</td>
<td>0</td>
<td>$C_{5}$</td>
<td>0.3837</td>
</tr>
<tr>
<td>$b_{10}$</td>
<td>0</td>
<td>$C_{6}$</td>
<td>0.3837</td>
</tr>
<tr>
<td>$b_{11}$</td>
<td>0</td>
<td>$C_{6}$</td>
<td>0.3837</td>
</tr>
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</table>

### III. Verification Example

An 11-order broadband extracted pole filter prototype with a return loss level $RL=22$ dB and normalized Tzs at $s_{01}=+j1.3253$ and $s_{02}=-j1.1968$ is designed to verify the proposed theory. The central frequency and bandwidth of the corresponding bandpass filter is 19.27 GHz and 2.35 GHz respectively.
The prototype circuit is shown in Fig. 7. The width of each resonator waveguide is set as 11mm. Therefore, the de-
normalized value of capacitance is derived as $C_x=0.3837$. The
synthesis results are shown in Table 4, Table 5. Some of the
synthesis details are omitted here due to page limit. The circuit
in Fig. 7 is then transformed to the distributed circuit, i.e. using
the waveguide TL sections for replacing the capacitors. An
efficient optimization procedure in the circuit domain is
performed before EM simulation. The optimized results are
shown in Fig. 8. They are compared with the results obtained
using the traditional extracted pole approach (also need circuit
optimization). As is shown, using traditional extracted pole
approach, the fundamental mode of the phase shifters will
generate the unwanted spikes. Those spikes are eliminated
using the circuit of this work. The far-out-band spikes are
caused by the higher order modes of the resonators. They can
be suppressed using the method in [8], which is beyond the
scope of this work.

The fabricated filter is shown in Fig. 9 and the measured
results compared with the EM simulation results are shown in
Fig. 10. Obviously, from the response in Fig. 10, in a relatively
large span of frequency, there is no extra spike induced by the
phase shifters as expected.

**IV. CONCLUSION**

This paper proposes a novel circuit configuration and
synthesis procedures to realize the unified extracted pole filter
without spikes in the stopband. The ideal phase shifters are
regarded as parts of resonators to eliminate unwanted spikes.
Besides, the filter design with the proposed approach is more
compact because the ideal phase shifters are absorbed into
resonators. The proposed approach is verified using a 11-pole
filter with 2 transmission zeros.

![Fig. 7 Low-pass prototype of 11-2 broadband extracted pole filter.](image)

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