High-Frequency Filter Design

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1. OBJECTIVES

- To apply the insertion loss method to design a lumped prototype of a low-pass filter starting from its design specifications.
- To implement an ideal lumped prototype of a low-pass filter as a realistic microstrip filter with open stubs using Richard's transformation, Kuroda's identities and Gupta's formulas.
- To implement a lumped prototype of a low-pass filter as a stepped impedance microstrip filter.
- To observe the limitations of these microstrip filters using a high-frequency circuit simulator and a full-wave EM simulator, contrasting the main differences in filter responses.
- To get familiar with the main characteristics of the high-frequency circuit simulator APLAC.
- To get familiar with the main characteristics of the full-wave EM simulator Sonnet.

2. COMPONENTS AND INSTRUMENTATION

- A numerical software tool: Matlab, Octave, Scilab, or something similar.
- The student version of the high-frequency circuit simulator APLAC.
- The EM simulator Sonnet Lite.

3. THEORETICAL PROCEDURE

1. Using the insertion loss method, design a low-pass filter prototype with the following specifications: a) cutoff frequency at 5 GHz; b) minimum insertion loss of 20 dB at 8 GHz; c) Chebyshev response with ripple of 0.5 dB; d) reference impedance of 50 Ω.

2. Implement the filter prototype with ideal lumped components. Simulate the filter in APLAC, plotting |S11| and |S21| from 1 MHz to 10 GHz in dB as well as in linear scale. Check that the filter satisfies all the design specifications.

3. Using Richard's transformation, implement the filter prototype with ideal lossless transmission lines on air (εr = 1). Using Kuroda's identities, transform the filter such that only shunt-connected open stubs are used. Simulate the filter in APLAC, plotting |S11| and |S21| from 1 MHz to 10 GHz in dB as well as in linear scale. Check that the filter satisfies all the design specifications.

4. Neglecting losses and metal thickness, implement the previous filter in microstrip technology using Gupta's formulas [1]. All microstrip lines are on a dielectric substrate with relative dielectric constant εr = 4.12. The substrate height is H = 0.25 mm. Simulate the filter in Sonnet Lite, plotting |S11| and |S21| from 1 MHz to 10 GHz in dB as well as in linear scale. Use a sufficiently low resolution such that you do not exceed the 16 MB limit of this version of the EM simulator. Compare in the same figure APLAC's responses with ideal transmission lines (from step 3) and new Sonnet's responses, for both |S11| and |S21| (in two separated figures).

5. Simulate again the previous filter in Sonnet Lite, but now considering that the loss tangent of the dielectric substrate is tan δd = 0.01, and that all metallic traces (including the ground plane) use copper with conductivity σCu = 5.8×10⁷ S/m. Plot |S11| and |S21| from 1 MHz to 10 GHz in dB as well as in linear scale. Compare in the same figure APLAC's response with ideal transmission lines (from previous step) and Sonnet's responses, for both |S11| and |S21| (in two separated figures).

6. Using the stepped impedance technique, implement the original filter prototype (from Step 1) with ideal lossless transmission lines on air (εr = 1) using a HighZ-LowZ configuration. Simulate the filter in APLAC, plotting |S11| and |S21| from 1 MHz to 10 GHz in dB as well as in linear scale. Check that the filter satisfies all the design specifications.

7. Neglecting losses and metal thickness, implement the previous stepped impedance filter in microstrip Simulate again the previous filter in Sonnet Lite, but now considering that dielectric losses (tan δd = 0.01) and metallic losses (σCu = 5.8×10⁷ S/m). Plot |S11| and |S21| from 1 MHz to 10 GHz in dB as well as in linear scale. Compare in the same figure APLAC's responses with ideal transmission lines (from step 6) and new Sonnet's responses, for both |S11| and |S21| (in two separated figures).
4. DESIGN & SIMULATIONS

We start to calculate the low-pass filter prototype by choosing the order based on the specifications of (1) in the Theoretical Procedure section by using the following figure (Fig. 1).

Since, \( \frac{w_c}{W_1} = 0.6 \) we zoom in the previous table and locate that point. (Fig. 2)

Which means that by choosing an order greater than 4 we cover the minimum insertion loss of 20 dB at 8 GHz.

![Fig. 1: Attenuation in Chebyshev filter with 0.5dB ripple of n-th order.](image)

![Fig. 2: Zoomed in 0.6.](image)

We will choose a fifth order filter to keep the last impedance the same as the characteristic impedance. Fig. 4 displays the table of a Chebyshev prototype values with 0.5 dB [2].

As the circuit components are defined as:

For a capacitor: \( \frac{g_k}{w_c Z_o} \) and for an inductor: \( \frac{Z_o g_k}{w_c} \)

The following MATLAB / GNU Octave script calculates the components for both prototype topologies (source series and shunt source) with a characteristic impedance of 50-Ω.

```matlab
% Low-Pass Filter Prototype
% a) Cutoff frequency at 5GHz
% b) Minimum Insertion Loss of 20dB at 8GHz
% c) Chebyshev response with ripple of 0.5dB
% d) Reference impedance 50-Ω
clc; clear all; close all;
fc = 5e9;
Zo = 50;
ILmin = 20;
f_IL = 8e9;
epsilon_r = 1;
c = 0.3e9;
lambda = c/(sqrt(epsilon_r)*fc);
lambda_8 = lambda/8;
N = 5;
% Filter Order
% Ideal Lumped Components Series Source
C1 = (g1/(2*pi*f*fc*Zo));
L2 = (Zo*g2)/(2*pi*f*fc);
C3 = (g3/(2*pi*f*fc*Zo));
L4 = (Zo*g4)/(2*pi*f*fc);
C5 = (g5/(2*pi*f*fc*Zo));
% Ideal Lumped Components Shunt Source
L1 = (Zo*g1)/(2*pi*f*fc);
C2 = (g2/(2*pi*f*fc*Zo));
L3 = (Zo*g3)/(2*pi*f*fc);
C4 = (g4)/(2*pi*f*fc*Zo);
L5 = (Zo*g5)/(2*pi*f*fc);
```

Which values end up to the following circuits (Fig. 5 and Fig. 6)

![Fig. 5: Shunt-source prototype.](image)

![Fig. 6: Series-source prototype.](image)
By utilizing APLAC HF Simulator, we get the following curves (Fig. 7 & Fig. 8).

We can appreciate there is no difference in a lumped elements simulation and hence choose the series source topology as it becomes easier to implement.

The design characteristics are therefore also met by both topologies.

We can appreciate the -0.5 dB cutoff point in the transmission |S21|, which was expected to be 5 GHz (Fig. 9).

And an attenuation greater than 20dB at 8GHz is also satisfied.
The next step is to change the filter with lossless transmission lines, by using Richard's transformation on air (\(\varepsilon_r = 1\)).

By replacing the capacitors as transmission lines ended as open circuits, and inductors as transmission lines ended in short-circuit.

\[
\begin{align*}
L &= Zo \\
C &= \frac{1}{Zo}
\end{align*}
\]

Whose length is \(\frac{\lambda}{8}\), to normalize the frequency.

We calculate the transmission lines characteristic impedances by running the following MATLAB / GNU Octave (having followed this report and the previous workspace open).

```matlab
% Richard's Transformation Series Source
Zo1_series = Zo/g(1);
Zo2_series = Zo*g(2);
Zo3_series = Zo*g(3);
Zo4_series = Zo*g(4);
Zo5_series = Zo/g(5);
```

And now we apply Kuroda’s identities (Fig. 11) to replace the transmission lines so that only shunt-connected open stubs are used.

Two of the four different identities were used.
We start by applying Kuroda’s Identity A to the input and output (1/g₁ and 1/g₅) in parallel with the normalized input and output transmission lines (Fig. 14).

This was done to make it possible to add a transmission line to the inductor formed by g₂ and g₄ (Fig. 15).

After this is done to both sides and applying Kurodaś Identity B we end up with the circuit shown in Fig. 16.

And simulating this circuit in APLAC gives us the following transmission and reflection plots (Fig. 17).

According to such simulation plots (Fig. 17), the cut-off frequency remains at 5 GHz, with greater than 20 dB attenuation at 8 GHz, 0.5 dB ripple and connected to a reference system of 50-Ω.

One thing to notice is that this implementation has a higher roll-off than the one with lumped components.
The next step is to implement such design in microstrip technology, at first neglecting losses and metal thickness during the simulation.

Using APLAC microstrip calculator we fill the following table (Fig. 18) with their corresponding physical lengths by taking into account \( \varepsilon_r = 4.12 \) and the substrate height of \( H = 0.25 \) mm.

<table>
<thead>
<tr>
<th>( Z ) [Ω]</th>
<th>Width [m]</th>
<th>( \varepsilon_r )</th>
<th>( \lambda )</th>
<th>Length [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z1</td>
<td>129.3118</td>
<td>5.45E-05</td>
<td>2.8</td>
<td>4.482107E-03</td>
</tr>
<tr>
<td>Z2</td>
<td>81.5212</td>
<td>1.98E-04</td>
<td>2.95</td>
<td>3.666696E-03</td>
</tr>
<tr>
<td>Z3</td>
<td>24.0329</td>
<td>1.43E-03</td>
<td>3.46</td>
<td>4.032025E-03</td>
</tr>
<tr>
<td>Z4</td>
<td>79.9588</td>
<td>2.07E-04</td>
<td>2.96</td>
<td>3.59286E-03</td>
</tr>
<tr>
<td>Z5</td>
<td>19.6788</td>
<td>1.84E-03</td>
<td>3.54</td>
<td>3.986205E-03</td>
</tr>
</tbody>
</table>

![Fig. 18: Microstrip parameters for the Richard’s – Kuroda’s transformations.](image)

And proceed to draw and implement the circuit on Sonnet Lite (Fig. 19).

![Fig. 19: Physical implementation of a filter using Richard’s – Kuroda’s transformations in Sonnet Lite.](image)

And for easier comparison we look at the simulation from the lossless transmission lines from APLAC (Fig. 21).

The bandwidth is identical and remains at 5 GHz.

An easy to spot difference would be the retransmission bump at 9.5 GHz in the microstrip implementation (Fig. 20) compared to the lossless transmission line but this is considered as noise floor in the numerical calculations of the software as it is in the range of -90 dB approximately.
To compare the results even further, we will now take into account the loss tangent of the dielectric substrate (\( \delta_d = 0.01 \)) and all the metallic traces with cooper conductivity \( \sigma_{Cu} = 5.8 \times 10^7 \text{ S/m} \).

Both can be found as Sonnet Lite simulation parameters. The simulation plots of such settings are in Fig. 22.

The loss tangent and metal losses produced almost no radical changes in the electro-magnetic simulation.

The bandwidth is reduced from 5 GHz to 4.983 GHz, and the attenuation at 8 GHz is higher in the lossy simulation; 83.14 dB vs 76.75 dB. It can also be seen that the transmission only reaches 1 (linear) at relatively low frequency and only approaches 1 after that and never reaching it.
The prototype done in step 1 (Fig. 25) will be implemented as a stepped impedance filter, where:

- Series inductors are replaced by high-impedance transmission lines ($Z_{\text{high}}$).
- Parallel capacitors are replaced by low-impedance transmission lines ($Z_{\text{low}}$).
- Lengths of the transmission line sections are calculated:

$$\beta l = \frac{g_l}{Z_{\text{high}}}$$

(for an inductor).

$$\beta l = \frac{g_l}{Z_{\text{low}}}$$

(for a capacitor).

The calculations are summarized in the following table (Fig. 26).

<table>
<thead>
<tr>
<th>$Z$ [Ω]</th>
<th>Width [m]</th>
<th>$\varepsilon$</th>
<th>$\lambda$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zo</td>
<td>50</td>
<td>5.02E-04</td>
<td>3.15</td>
<td>3.38E-02</td>
</tr>
<tr>
<td>Zlow</td>
<td>10</td>
<td>4.06E-03</td>
<td>3.75</td>
<td>3.10E-02</td>
</tr>
</tbody>
</table>

Where according to the schematic:

$$Z_{\text{low}} = g_1g_2g_3$$

$$Z_{\text{high}} = g_2g_4$$

$$Z_{\text{low}} = g_3$$

And simulating such implementation in APLAC, we obtain the following plots.

The roll-off of such implementation is way less steep than the Richard’s – Kuroda’s transformation from lumped components.

But the 20 dB of attenuation at 8 GHz still comply with our design requirements.

Drawing this in APLAC results in the following schematic (Fig. 27).
To implement the filter in microstrip technology we also make use of APLAC microstrip calculator and fill the following table (Fig. 28).

<table>
<thead>
<tr>
<th>$Z_0$ (Ω)</th>
<th>Width [mm]</th>
<th>εr</th>
<th>λ</th>
<th>β</th>
<th>Norm. Width [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>5.02E-04</td>
<td>3.15</td>
<td>3.38E-02</td>
<td>185.86</td>
<td>0.50229</td>
</tr>
<tr>
<td>10</td>
<td>4.06E-03</td>
<td>3.75</td>
<td>3.10E-02</td>
<td>202.79</td>
<td>0.06000</td>
</tr>
<tr>
<td>150</td>
<td>3.13E-05</td>
<td>2.77</td>
<td>3.61E-02</td>
<td>174.29</td>
<td>0.03134</td>
</tr>
</tbody>
</table>

Fig. 29: Microstrip calculations for the stepped impedance filter.

And the implementation using Sonet Lite (Fig. 30) with the following parameters: εr = 4.12 and the substrate height of H = 0.25 mm.

Comparing Sonnet Lite (Fig. 31) vs APLAC (Fig. 32) simulations we can observe that they are practically the same with no radical changes between them.

And by simulating it in Sonnet Lite, we obtain the following plots (Fig. 31).
And finally we will now take into account the loss tangent of the dielectric substrate ($\delta_d = 0.01$) and all the metallic traces with cooper conductivity $\sigma_{cu} = 5.8 \times 10^7 S/m$.

The dielectric and metal losses simulation has a notable overall attenuation during the pass-band. It only reaches 1 (linear scale) at practically DC (Fig. 33).

The reflection is even worse at this point (considering that the reflection coefficient is higher than the Richard’s – Kuroda’s transformation implementation.

The cut-off frequency remains almost the same in the three cases. And the attenuation at 8 GHz remains higher than 20 dB.
5. CONCLUSIONS

The design of filters by utilizing prototypes is so convenient. It can be seen that the method of physical implementation of high frequency filters can greatly determine subtle but particular characteristics that can be used as an advantage in the design.

Both designs complied with our requirements but the Richard's – Kuroda transformed filter had a steeper roll-off and was more robust to dielectric and metal losses.

A bigger window in the filter response simulations clearly shows the cyclic behavior of the filters. (Fig. 36) even if the base design was merely a low-pass.

![S-Parameter Analysis](image)

*Fig. 36: Behavior repeating at four times the cut-off frequency.*

Electro-magnetic simulations software such as APLAC is very powerful once you get the hang on it. It is of great recommendation to start working and simulating with various kind of software to compare your results and make sure you are going in the right direction of the design.

6. REFERENCES

