Project 2 - Bandpass Filter Design

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May 6, 2017

Background

The goal of this project was to create a bandpass filter with the following specifications listed below.

- Center frequency: 5 GHz
- 3 dB FBW: 20%
- Insertion Loss: <3 dB
- Pass-band Ripple: <2 dB
- Out of Band Rejection: >30 dB
- Shape Factor: <3

The substrate specified was Rogers 5880 HH with a top/bottom copper cladding of 17 micrometers, dielectric constant of 2.2, and a dielectric thickness of 0.062 inches. The bandpass filter was to be inserted in the same 1.25 inch by 1.5 inch test fixture (measured with a 50-ohm system) from the previous project.

Design Process

The initial design began with using the Equal Ripple (Chebyshev) filter for a sharper cutoff but with a tradeoff of having larger ripples. Upon the realization of the errors that arise when shifting the filter from a lowpass to a bandpass and that Kuroda's identity for the transformation of a series capacitor to a shunt element was not that simple, the design had to be abandoned. Instead, a coupled line filter was used. The implementation of a coupled line filter was much simpler, as the bandpass configuration was readily available (as opposed to a lowpass that had to be shifted). By treating the top-left side of the coupled line as the input and the bottom-right side as the output, a bandpass configuration is complete. A sample image of cascading multiple coupled line filters for a bandpass response is seen below.

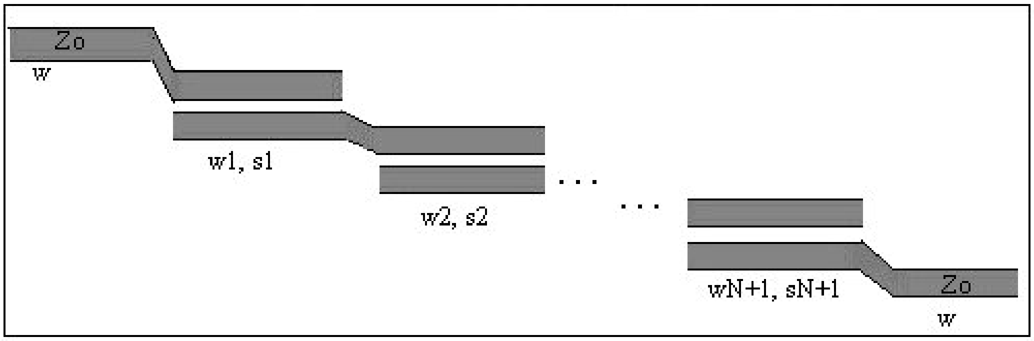

Figure 1: Sample Bandpass Implementation using Coupled Line Filters

Each filter had N+1 coupled lines. Our filter was designed with N = 2, meaning we had three coupled lines and therefore 3 g_n values (or lowpass prototype values). There is a tradeoff with choosing different values of N: a higher N gives a worse insertion loss and larger ripples while a lower N gives a smaller shape factor and out-of-band rejection loss. Due to board size restrictions, we only tested our board with N = 2, so we had three sections. As a result, a lot of tweaking had to be done to get close to the desired shape factor. The even and odd mode impedances had to be calculated for each line and then the LineCalc tool was used to convert that into actual width and length values for the coupled lines. The calculations to get those impedance were the following:

$$J_1 = \frac{\sqrt{\frac{\pi\Delta}{2g_1}}}{Z_0} \tag{1}$$

$$J_2 = \frac{\pi\Delta}{2Z_0\sqrt{g_2 g_1}} \tag{2}$$

$$J_3 = \frac{\sqrt{\frac{\pi\Delta}{2g_3 g_2}}}{Z_0} \tag{3}$$

$$Z_{0e} = Z_0[1 + JZ_0 + (JZ_0)^2] \tag{4}$$

$$Z_{0o} = Z_0[1 - JZ_0 + (JZ_0)^2] \tag{5}$$

The prototype values were: $g_1 = 1.4029$, $g_2 = 0.7017$, $and\, g_3 = 1.9841$. Δ corresponds to the FBW, which is 20% (or 0.2) for our design. Designing this for a larger bandwidth may have helped meet the requirement when simulating the schematic and board, however, it made it much harder to meet the shape factor requirement, so we stuck with 0.2 for this value. Using the equations above, the even and odd impedances for the three sections of the line were calculated. The results are seen in Table 1 below.

Coupled Line	g_n	J_n	Z_{0e}	Z_{0o}
1	1.4029	0.009464	84.8559	73.5359
2	0.7017	0.006333	70.8459	39.1809
3	1.9841	0.009501	85.03161	37.5311

Table 1: Odd and Even Impedances for the Coupled Line

Unfortunately, when put into ADS, this design did not do too well with the shape-factor specification. Using the results from Table 1, the resulting bandpass response is seen below in Figure 3. The ADS schematic for the calculated design is seen in Figure 2.

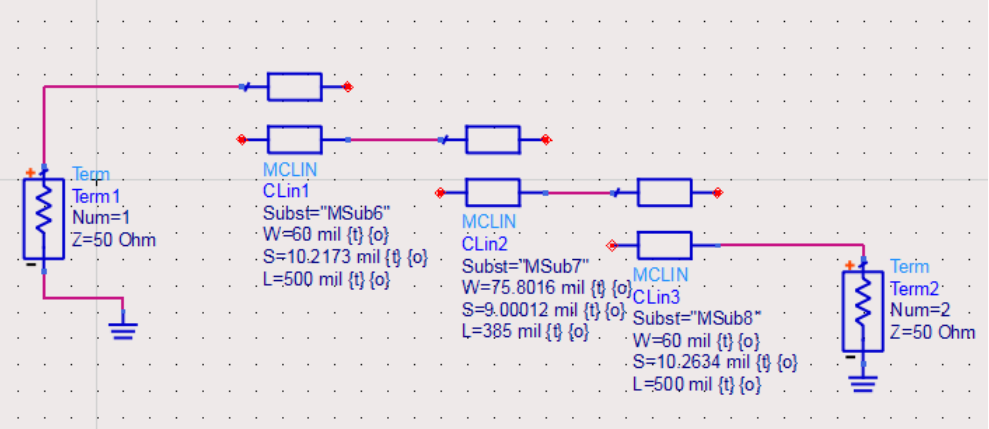

Figure 2: Calculated Design Schematic

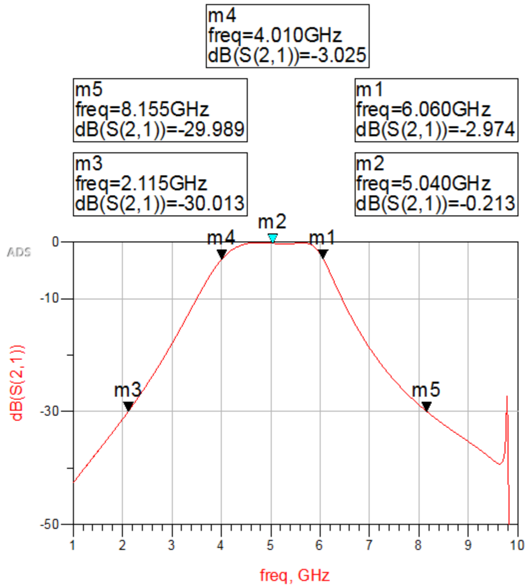

Figure 3: S21 Result from the Calculated Design

The bandpass is clearly too wide and needed to be narrower. Hence, the optimization tool was used to refine the shape factor by providing it with the desired specs and giving them “weights” of importance according to which ones were more difficult to achieve. The optimization changed the widths and lengths quite drastically from what they were before, however, the results, seen in Figure 5, were slightly better. The shape factor did not change that much and, as seen in the board layout simulation, did not meet the specification. The calculation of the shape factor is discussed later. The ADS schematic for the optimized design is seen in Figure 4.

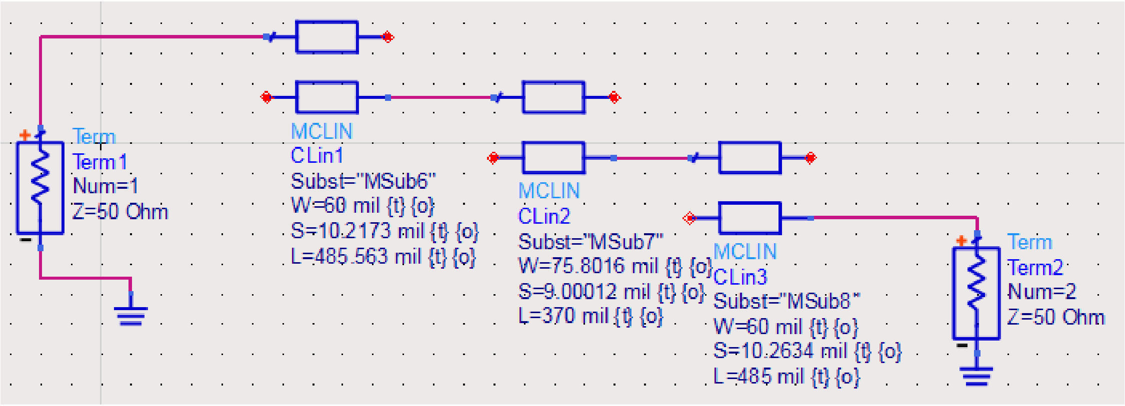

Figure 4: Optimized Design Schematic

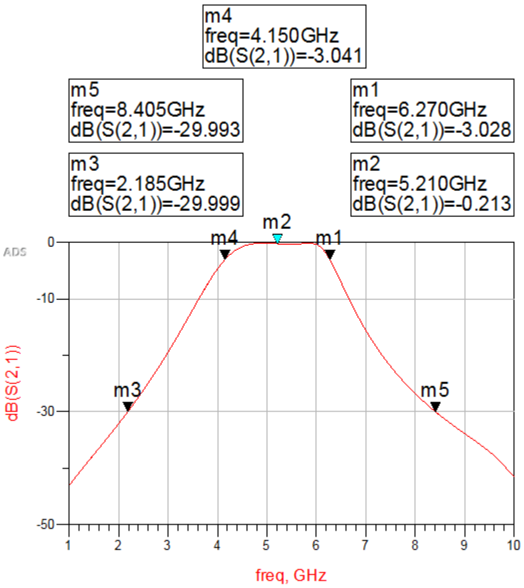

Figure 5: S21 Result from the Optimized Design

Next, the board layout was generated. To fit the desired test unit dimensions of 1.25 inches by 1.5 inches, the coupled line filter had to be placed diagonally across the two sides of the board. The polygon tool was used to properly fit the filter on the pins. This tool simply adds copper according to the shapes drawn on the specified layer. Using this approach, instead of adding bends to the schematic and placing them accordingly, gave us more flexibility in quickly changing the design to get better results. The board layout is seen in Figure 6 and the resulting S21 plot is seen in Figure 7.

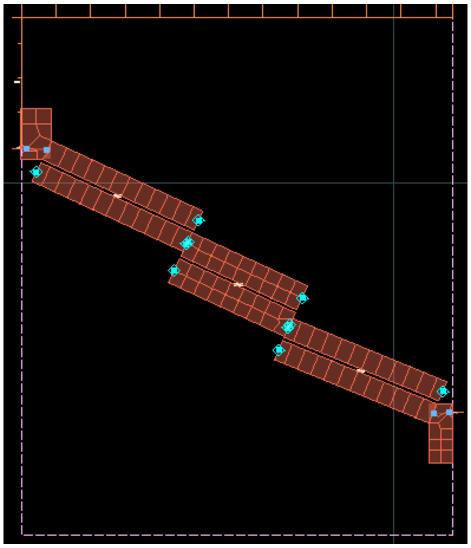

Figure 6: Board Layout

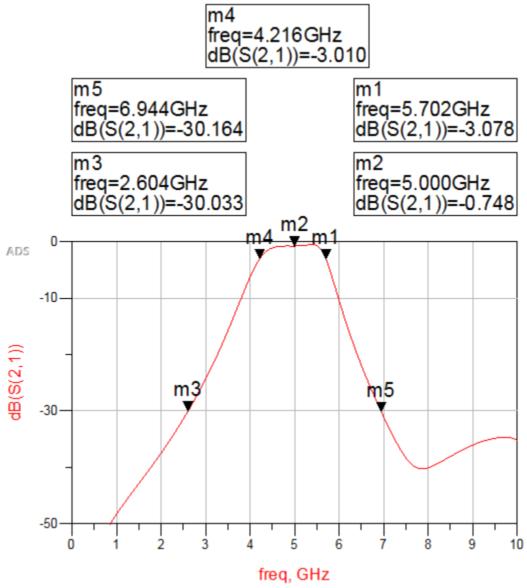

Figure 7: S21 Result from the Board Simulation

This design did not meet the shape factor specification, unforunately. The value of S21 at marker m3 in Figure 7 is at 2.604 GHz; this is used for the 30 dB bandwidth reference since it is what makes the bandpass wider (the marker at m5 is closer to the center frequency). Therefore, the 30 dB BW was $2 \times (5 - 2.604) = 4.792\, GHz$. The 3 dB BW was calculated using the m1 marker, instead of the m4 marker, since it makes the 3 dB BW smaller (the opposite of what we want). Thus, the 3 dB BW was calculated to be $2 \times (5.702 - 5) = 1.404\, GHz$. Hence, the shape factor was the $\frac{4.792}{1.404} = 3.41$. Although this did not meet the spec, it was quite close. The same calculation was used to calculate the shape factor for our actual measurement results.

Results

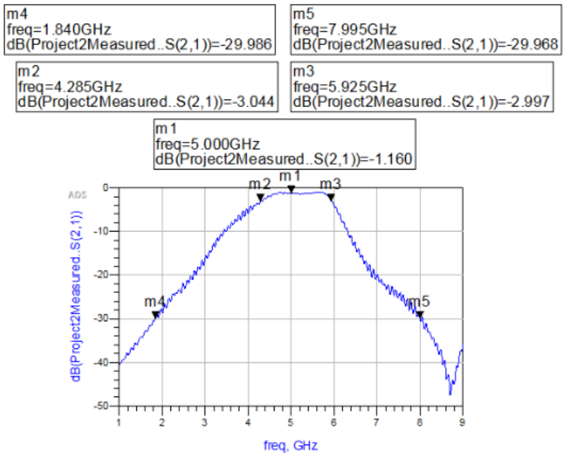

Figure 8: Measurement Results

Table 2 below shows the results from the measurement versus those from the specifications. The plot of the measurement results is seen in Figure 8.

Result	FBW	Insertion Loss (dB)	Passband Ripple (dB)	Shape Factor	Out of Band Rejection
Specification	20%	<3 dB	<2 dB	<3	>30 dB
Measurement	28.6%	1.160 dB	$1.387 - 0.909 = 0.478$ dB	$\frac{59.9}{14.3} = 4.189$	>30 dB

Table 2: Results Summary

All the specifications were met except that of the shape factor. This was due to the fact that a low number of coupled line sections was used for a tradeoff of less ripples in the output. Less restrictions on the board size could have provided us with more room in terms of design choices. Compared to the previous project, the measurement results were quite close to the board simulation results. As one would expect with any measurement, it did not completely match the simulation due to things like calibration, losses, etc. Overall, our bandpass filter design was quite succesful and met all the given specs but one.