SYRACUSE UNIVERSITY

Design, Optimization, Fabrication, and Measurement of an Edge Coupled Filter

Project 2

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12/08/2011

Abstract

The design, optimization, fabrication, and measurement of an edge coupled Bandpass filter realized in Microstrip technology is presented. The design process begins with written filter requirements and finishes with a fabricated circuit. The presented process includes the estimation of filter parameters using analytical formulas, the simulation of ideal and Microstrip transmission line models in a circuit simulator, the simulation of Microstrip models in a full wave 3D simulator, and the fabrication of the final design using a rapid prototype milling machine. An extensive comparison of the response obtained from simulation phases and the final fabricated design is presented. The author's reflections regarding such inaccuracies present between the various simulators and the fabricated results are included.

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Introduction

In this report an edge coupled filter is designed, simulated, and fabricated in microstrip technology. The center operating frequency for the filter is 4.0 GHz with a bandwidth of 15% based on the Chebychev filter approximation. In this report a design flow is presented that begins with a set of design requirements and finally concludes with a complete fabricated circuit.

The general theme of the design process is to begin with a high speed/low accuracy estimation and progressively add complexity. For each increase in complexity, the design must be tuned to counteract degradation introduced by the higher accuracy model. This process is more effective than tuning the final model because high accuracy models are very difficult and costly to design and tune directly.

The process of designing the filter includes the usage of empirical formulations, MATLAB [1] as an equation solver, Ansoft Designer™ [2] as the circuit simulator and Ansoft HFSS™ [3] as a full wave simulator. The final design is fabricated, measured and compared to the HFSS simulation results.

Design Requirements

The center operating frequency for the filter is 4.0 GHz with a bandwidth of 15%. The minimum rejection at the normalized frequency ($\frac{\omega_t}{\omega_c}$ = 1.6) is required to be under 20dB. The maximum ripple allowed in the pass band is 0.05dB. No further filter requirements are provided.

The design must be fabricated with provided samples of a variety of Rogers RO/duroid materials, and the fabricated circuit must be measured using a network analyzer with results of measurement compared to final design results.

Procedure

Empirical Formulations

The analytical procedure for designing a Chebychev band pass filter (BPF) requires the initial design of a prototype Chebychev low pass filter (LPF). Frequency mapping is then used to derive the even-mode and odd-mode impedances of each section of coupled line for the BPF. The length of each line is a quarter wavelength of the center frequency [4].

The first step for designing any Chebychev filter is to determine the order of the filter. The filter order is the number of inductive and capacitive elements that should be included in the filter design. This can be determined with the following formulation

$$n = \frac{cosh^{-1}\sqrt{\frac{10^{\frac{L_{T'}}{10}} - 1}{K - 1}}}{cosh^{-1}\left(\frac{w_{T'}}{w_C}\right)}$$

where L_T is the minimum attenuation at frequency W_T, and K = 10^(L_{ar}/10), with L_{ar} being the maximum ripple in dB allowed in the pass band [4]. The order of the filter is a measure of the minimum number of elements to be included in the filter to realize the required amount of ripple in the pass band and attenuation at a frequency outside of the pass band. Additional elements may be included in the filter which will further improve the filter response at the cost of size and increased design time. The following equations are used to calculate the element values of each filter element. These equations will map to even-mode and odd-mode impedances using subsequent equations based on the cut-off frequency [4].

$$g_0 = 1$$

$$g_1 = \frac{2 * a_1}{\gamma}$$

$$g_k = \frac{4a_{k-1} * a_k}{b_{k-1} * g_{k-1}}$$

$$g_{n+1} = 1$$

$$\beta = ln\left[\coth\left(\frac{\mathrm{L_{ar}}}{17.37}\right)\right]$$

$$\gamma = sinh\left(\frac{\beta}{2n}\right)$$

$$a_k = sin\left(\frac{(2k-1)\pi}{2n}\right)$$

$$b_k = \gamma^2 + sin^2\left(\frac{k\pi}{n}\right)$$

The filter's transmission line network is made from parallel coupled lines (also called edge coupled lines) using microstrip technology. Frequency mapping is used to derive the impendences for each section of line using the following equations [4].

$$\omega' = \frac{1}{\omega_r}\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)$$

$$\omega_r = \frac{\omega_2 - \omega_1}{\omega_0}$$

$$\omega_0 = \sqrt{\omega_1 \omega_2}$$

In the above calculations, ω_r is the bandwidth, ω' is the normalized frequency of the prototype LPF (ω'_T/ω_C = 1.6), ω_1 and ω_2 are the band edge frequencies (equal ripple), ω_o is the center frequency, and ω is the frequency at which the minimum cutoff must be achieved. The results of performing these calculations with the specified design information indicate that desired minimum attenuation of 20dB must be achieved above 4.5 GHz signal frequency.

The length of each section of transmission line is the quarter wavelength at the center frequency. The even and odd mode impedance values for each section are calculated from the following set of equations [4]. The impedances that are used in this filter can be found in Table 1.

$$Z_{0e_{0,1}} = Z_{0e_{n,n+1}} = z_0\left[1 + \left(1 + \frac{g_1}{2} tan\emptyset\right)^{-1/2}\right]$$

$$Z_{0o_{0,1}} = Z_{0o_{n,n+1}} = z_0\left[1 - \left(1 + \frac{g_1}{2} tan\emptyset\right)^{-1/2}\right]$$

$$\emptyset = \left(\frac{\pi}{2}\right)\left(\frac{f_1}{f_0}\right)$$

$$Z_{0e_{k,k+1}} = s\left[N_{k,k+1} + \frac{K_{k,K+1}}{Z_0}\right]$$

$$Z_{0o_{K,K+1}} = s\left[N_{k,k+1} - \frac{K_{k,K+1}}{Z_0}\right]$$

Where

$$s = \frac{2 g_1 z_0}{2 + g_1 tan\emptyset}$$

$$N_{K,K+1} = \sqrt{\frac{K_{K,K+1}}{Z_0}^2 + \frac{tan\emptyset}{2}^2}$$

$$\frac{K_{01}}{Z_0} = \frac{1}{\sqrt{g_1}}$$

$$\frac{K_{K,K+1}}{Z_0} = \frac{1}{\sqrt{g_k g_{k+1}}}$$

Z_{0e1}	68.4513
Z_{0o1}	31.5487
Z_{0e2}	49.3823
Z_{0o2}	37.7759
Z_{0e3}	47.6918
Z_{0o3}	39.1149
Z_{0e4}	47.6918
Z_{0o4}	39.1149
Z_{0e5}	49.3823
Z_{0o5}	37.7759
Z_{0e6}	68.4513
Z_{0o6}	31.5487

Table 1: Calculated impedance values in ohms

Initial Design

Analytical results are used as a starting point for the ideal circuit models generated with Ansoft Designer™[1], the circuit simulator used. The ideal circuit model typically requires an amount of tuning to get it to meet design specifications and is then used as a starting point to generate a microstrip circuit model. The microstrip circuit model also requires an amount of tuning to get it to meet specifications.

Ideal Transmission Line Model

The initial design was created from ideal transmission lines in Ansoft Designer using the Filter Design Wizard (FDW). The FDW uses the center frequency, bandwidth, and the image impedance (set to 37Ω) to synthesize a filter. This value of image impedance was chose because it resulted in a filter with even and odd mode impedances most similar to the analytical results.

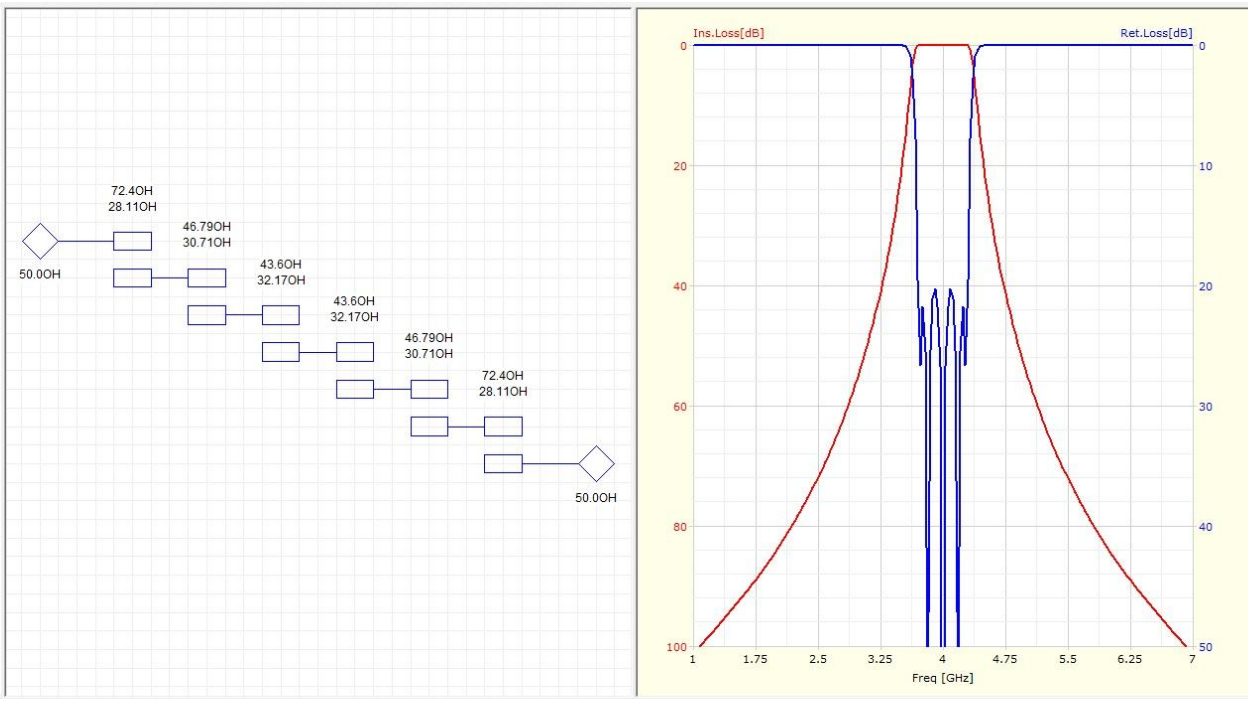

Figure 1: FDW for Chebyshev bandpass filter

Z_{0e1}	73.51
Z_{0o1}	28.8
Z_{0e2}	48
Z_{0o2}	31.55
Z_{0e3}	44.77
Z_{0o3}	33.04
Z_{0e4}	44.77
Z_{0o4}	33.04
Z_{0e5}	48
Z_{0o5}	31.55
Z_{0e6}	73.51
Z_{0o6}	28.8

Table 2: Impedance values from FDW in ohms

The filter object from Designer was converted to its electrical circuit model. Open circuit stubs with electrical lengths of zero were added to the ends of the ideal transmission lines to better represent the coupled-line model.

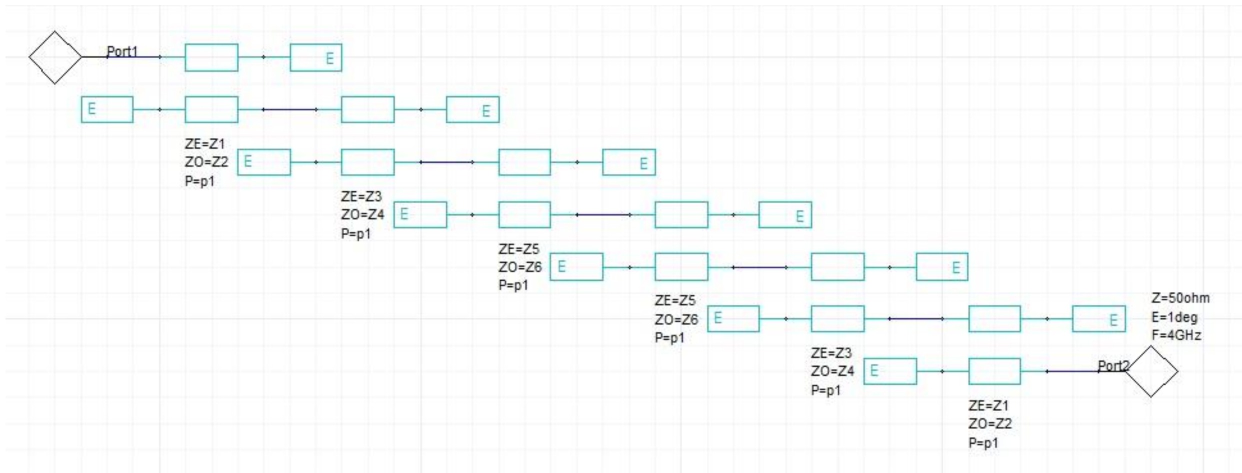

Figure 2: Electrical circuit model of 5th order Chebyshev bandpass filter made from ideal transmission lines

The BPF generated from the FDW already met the specifications for the project. The insertion loss is well below 25dB at 4 GHz and the ripple never exceeds 0.05dB.

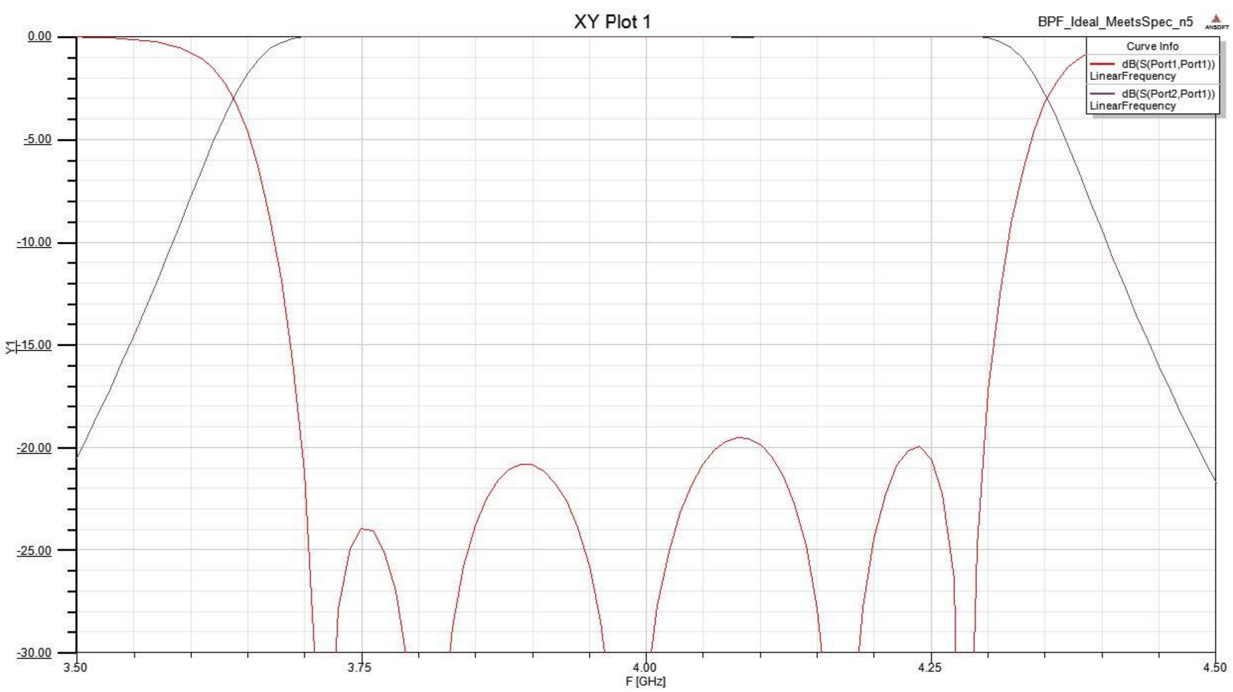

Figure 3: Insertion loss of Chebyshev bandpass filter made from ideal transmission lines

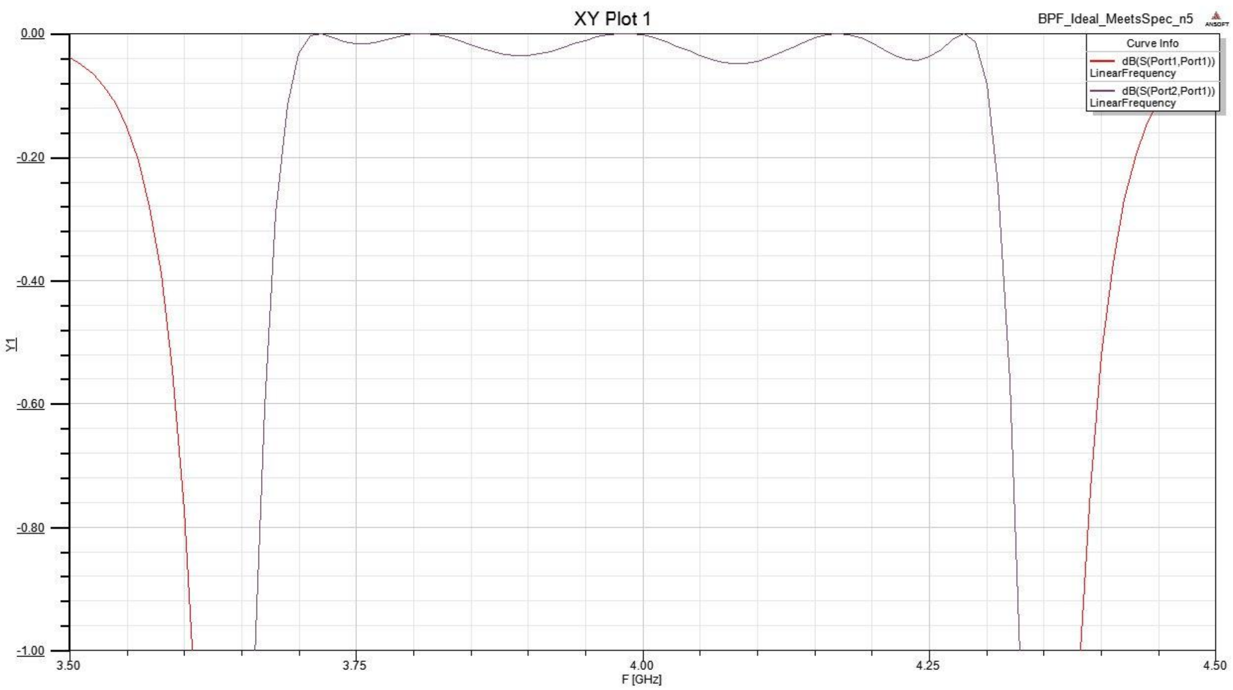

Figure 4: Ripple of Chebyshev bandpass filter made from ideal transmission lines

Microstrip Model

After designing an acceptable model of the filter in the ideal case, the design must be realized in microstrip stripline technology to better represent how the filter will respond in a real world scenario. The model used by Designer of two edge-coupled microstrip lines is represented in the figure below. There are two metallic strips on top of a substrate which is itself above a ground plane. Each trace has an independent width w (w1 and w2, but the model shows "w"), and the two are separated by a spacing s. The opposite ends of signal input or output are modeled as open, so no open stub is needed as with the ideal transmission line model.

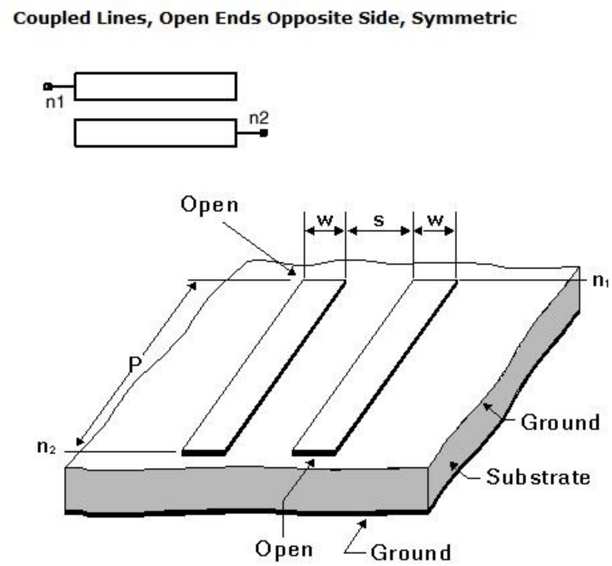

Figure 5: Model used by Designer for edge-coupled microstrip traces

The substrate material Roger 6006 was chosen out of the available materials in the lab. The selection of dielectric material was based around the synthesis resulting in the highest separation of the first coupled section of all the available sample materials, as it was known that the rapid prototype machine has a minimum milling bit size and that trace spacing will be forced to a minimum of this bit size. The Rogers 6006 sample available has a dielectric constant of 6.15 and a height of 50mil. Using the FDW, a microstrip Chebyshev filter was generated with a center frequency of 4 GHz.

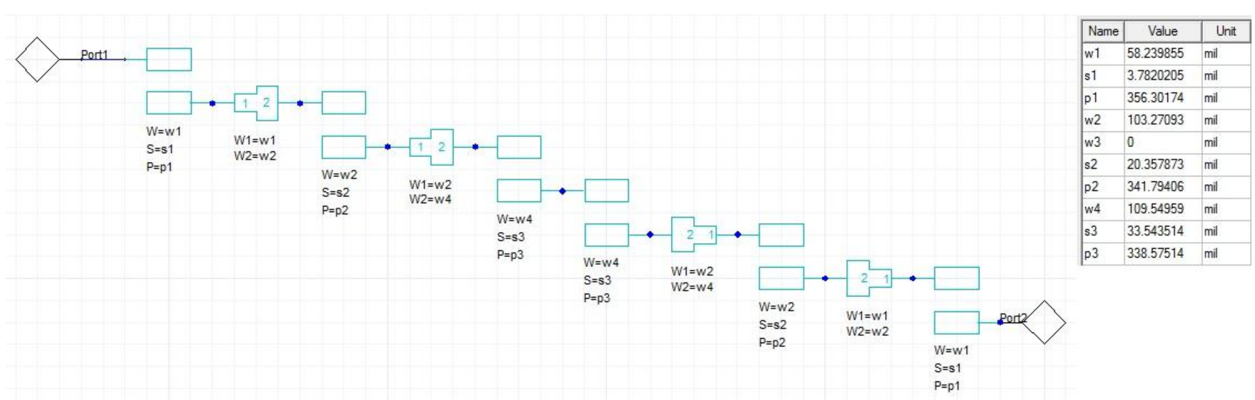

Figure 6: Chebyshev bandpass filter made from microstrip technology

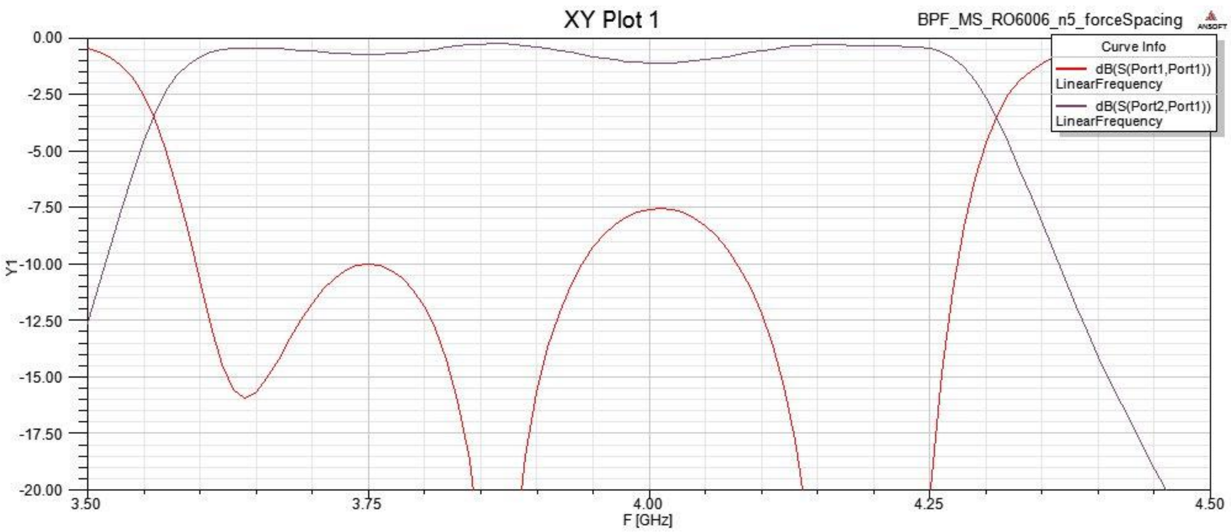

Figure 7: Response of Chebyshev bandpass filter made from microstrip technology

The synthesis results in a 3.78mil separation of the first coupled microstrip section. The discontinuity steps introduced a 50 MHz downwards shift of the center frequency. Also, the rapid prototype tool that will be used to fabricate this filter has a milling bit with a minimum diameter of 7mil.The FDW tool was rerun at 4.05 GHz to accommodate the shift and the 7mil constraint was also specified by the design team. The widths, lengths, and spacings of the internal sections were then manually tuned in order to meet the project specifications.

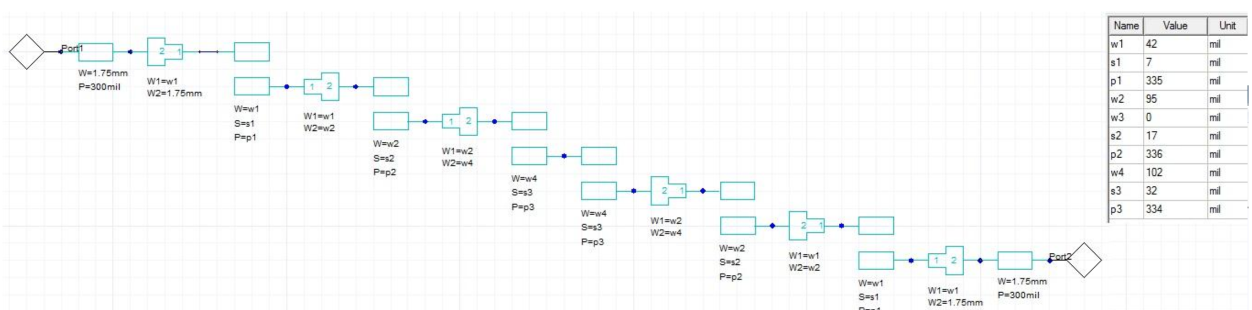

Figure 8: Tuned Chebyshev bandpass filter made from microstrip technology

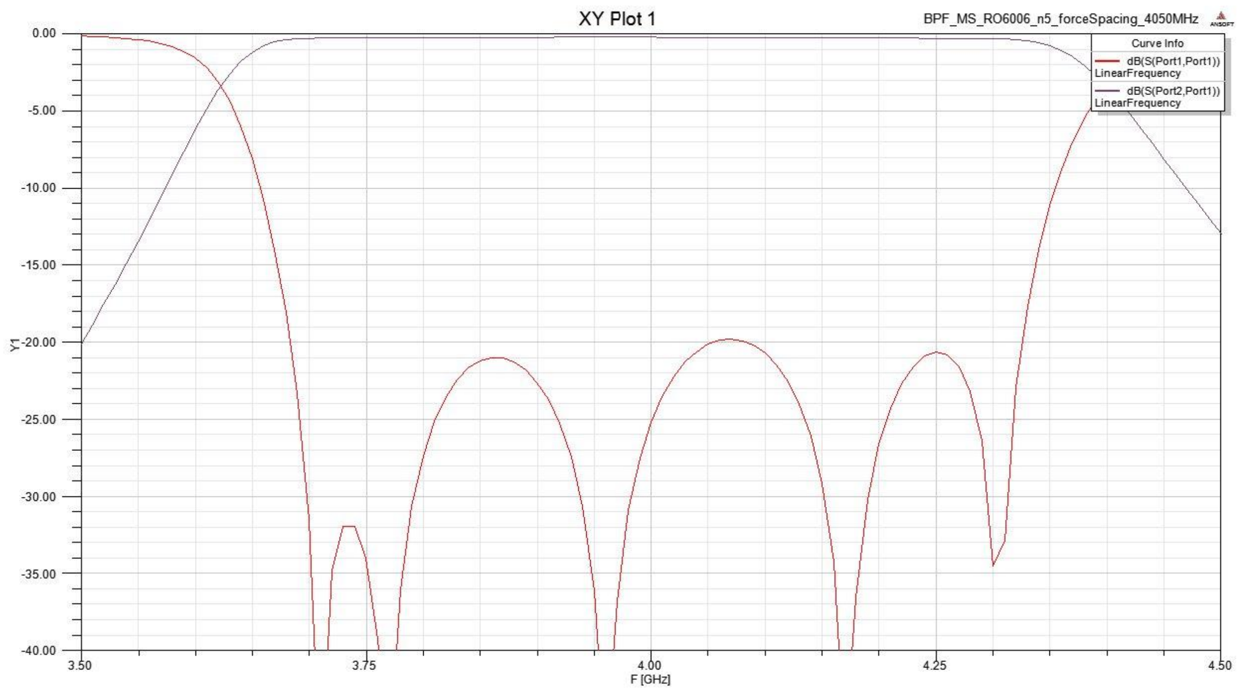

Figure 9: Response of tuned Chebyshev bandpass filter

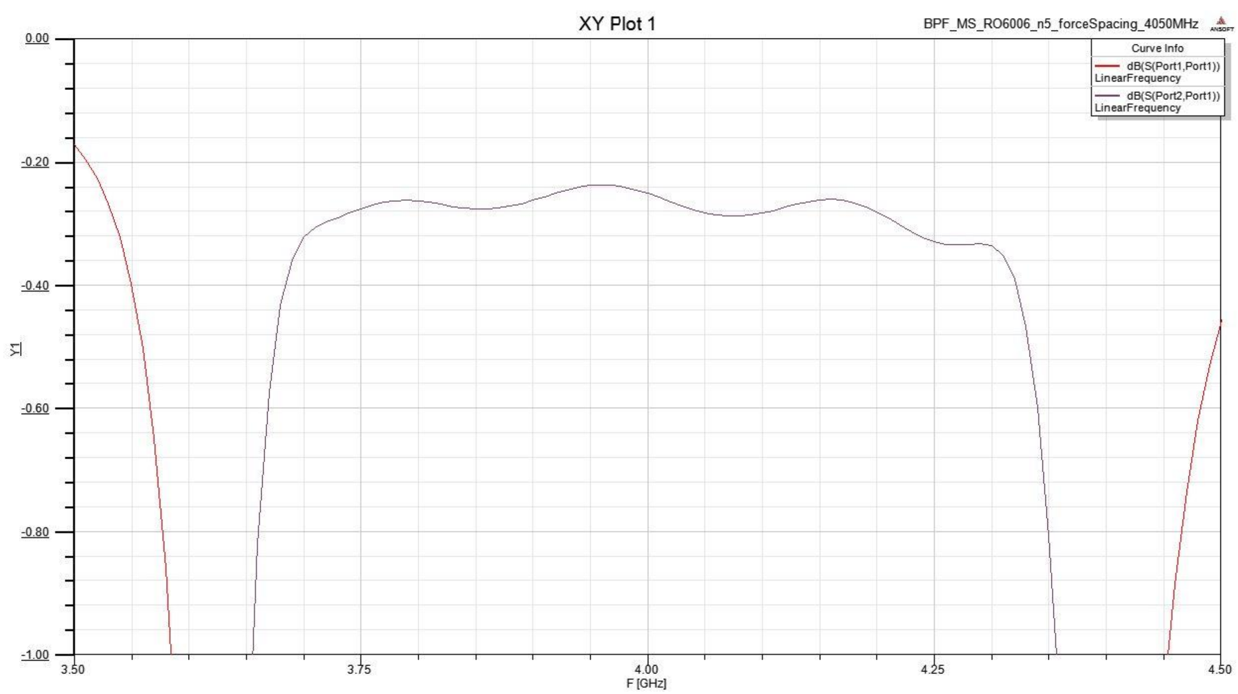

Figure 10: Ripple of tuned Chebyshev bandpass filter

HFSS Model

The physical structure in Ansoft Designer was exported to HFSS. The traces are copper with a thickness of 1.4mils. The substrate is Rogers 6006 with a height of 50mils. Two wave ports with widths of 252mils (6x the trace width) and heights of 400mils (8x the substrate height) were draw at either end of the filter. Because HFSS considers empty space to be a perfect conductor, an air box with a height of 500mils (10x the substrate height) was created on top of the substrate. The external surfaces of the air box are considered an air to perfect-conductor interface and can cause unwanted and unrealistic reflections. They were declared as radiation boundaries in HFSS, which effectively absorbs any wave incident normal to the surface.

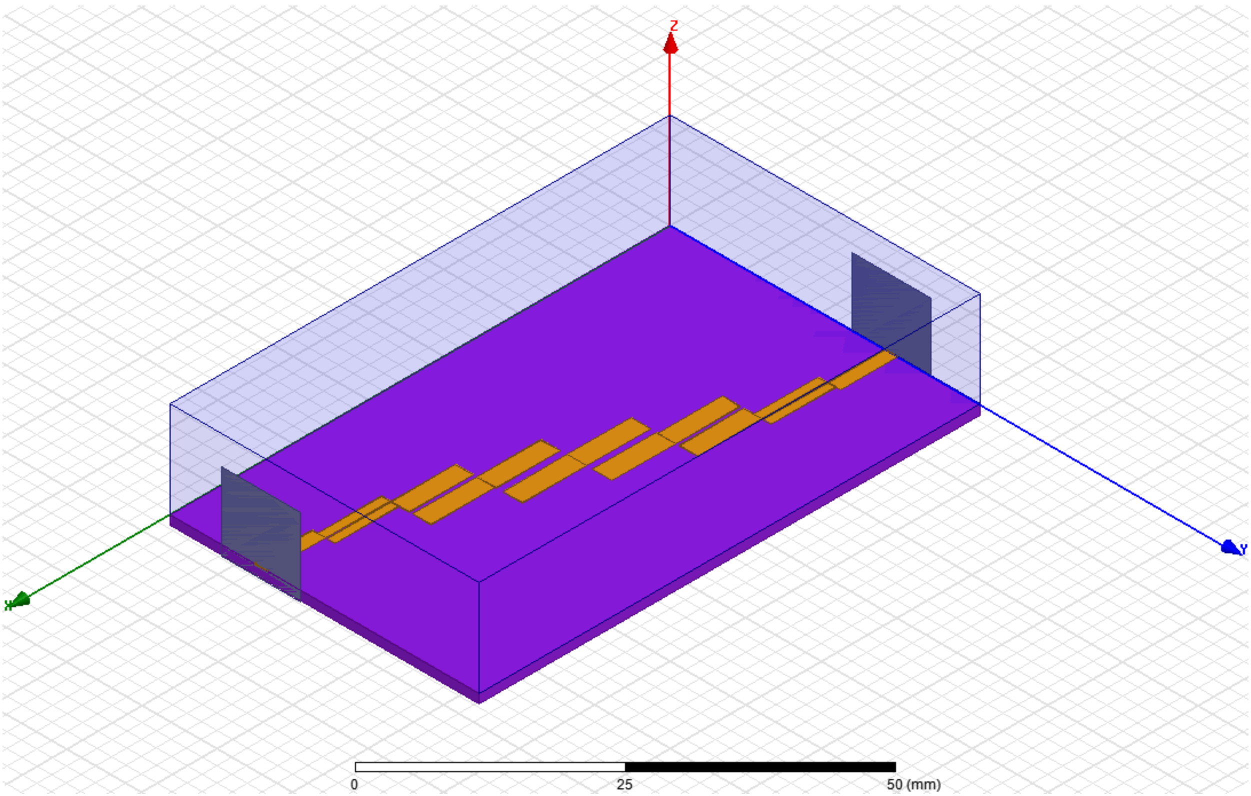

Figure 11: HFSS model of the Chebyshev bandpass filter

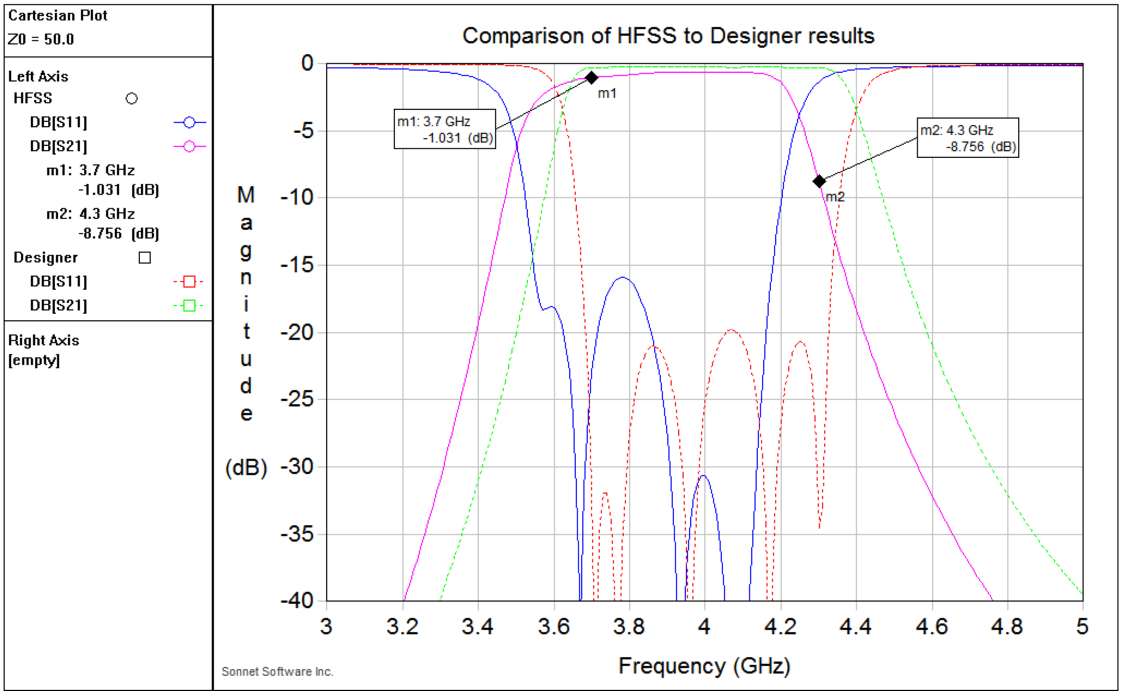

Figure 12: Comparison of HFSS and Designer results

The HFSS simulation introduces a shift of approximately 0.1 GHz when compared to Designer. It also no longer meets the requirement of and insertion loss of less than 20dB in the pass band. At this point, the design team decided to switch to a 6th order filter in order to finish the design and fabrication with measurement by the deadline with the best chance of meeting the specifications. There were no considerations of cost in terms of additional design time or of physical board real-estate by adding another order, as this was not specified in the project.

Redesign

After the decision to redesign the filter with a higher order of 6 was made, the analytical process used during the initial design was completed rapidly and accurately using the same Matlab script. The results of Z0o and Z0e, not shown here, are almost identical to that of the 5 order approach, except an additional coupling section is used to represent the increased order. This similar result of ideal filter design is evidence that, according to the formulation, a 5 order filter should be sufficient.

The filter design wizard (FDW) in Ansoft Designer was again utilized to formulate the lengths and widths of the physical circuit from given input of filter design and material properties. Rogers 6006 was again chosen as the dielectric, but the center frequency was chosen as 4.150 MHz. This frequency offset is in anticipation of the pass band center frequency being shifted downward by the simulations. It is expected that the results of Designer will present a shift of around 50MHz and of HFSS to simulate a further shift of 100MHz downward.

As it has already been shown that a 5 order ideal transmission line model is sufficient for the design, this step was bypassed for the 6-order redesign. The results of the FDW are immediately realized in microstrip to begin tuning for optimized performance. The previous Zi of 37 is not utilized during the redesign. Since our minimum spacing is 7mil, a Zi is chosen such that the minimum spacing of the filter exported from the FDW is above 7mil. This image impedance was Zi = 47. The results of the FDW are shown below

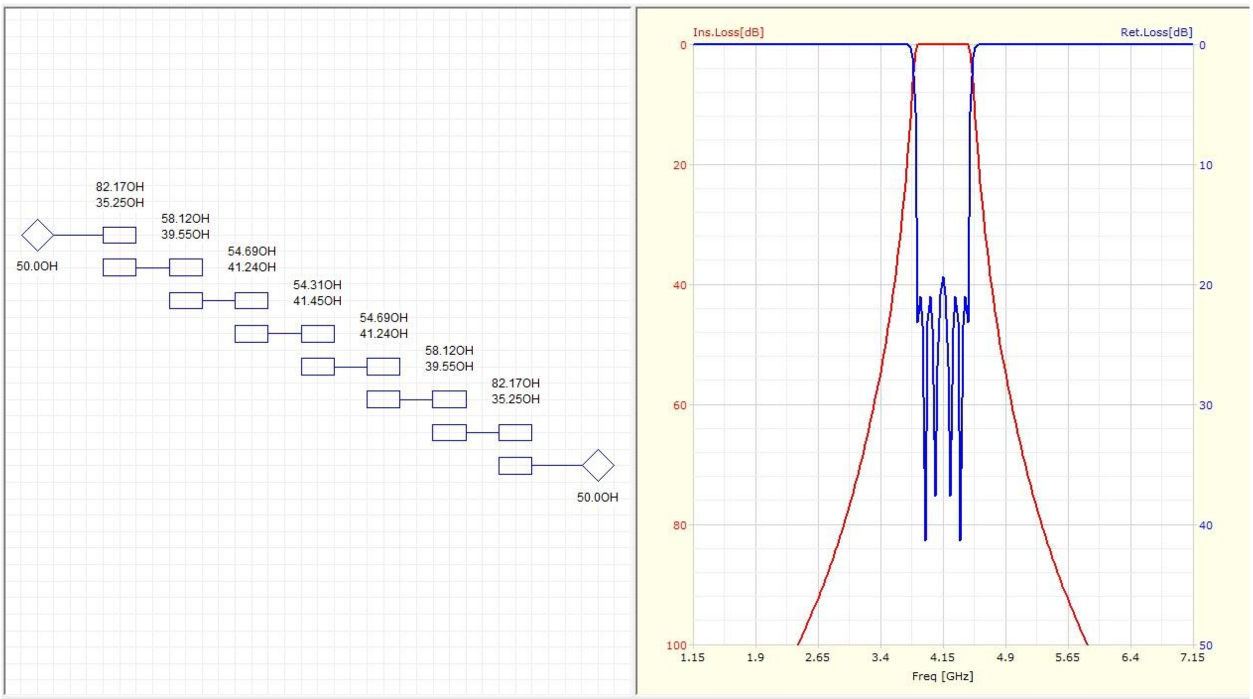

Figure 13: Result of Filter Design Wizard for n=6, fo = 4.150GHz, Rogers 6006

This filter is exported to microstrip and altered with 50Ω lines as input and output traces, along with microstrip steps. The circuit diagram, parametric values, and results of the first optimization in Designer of the 6-order filter using microstrip technology are demonstrated in the figures below.

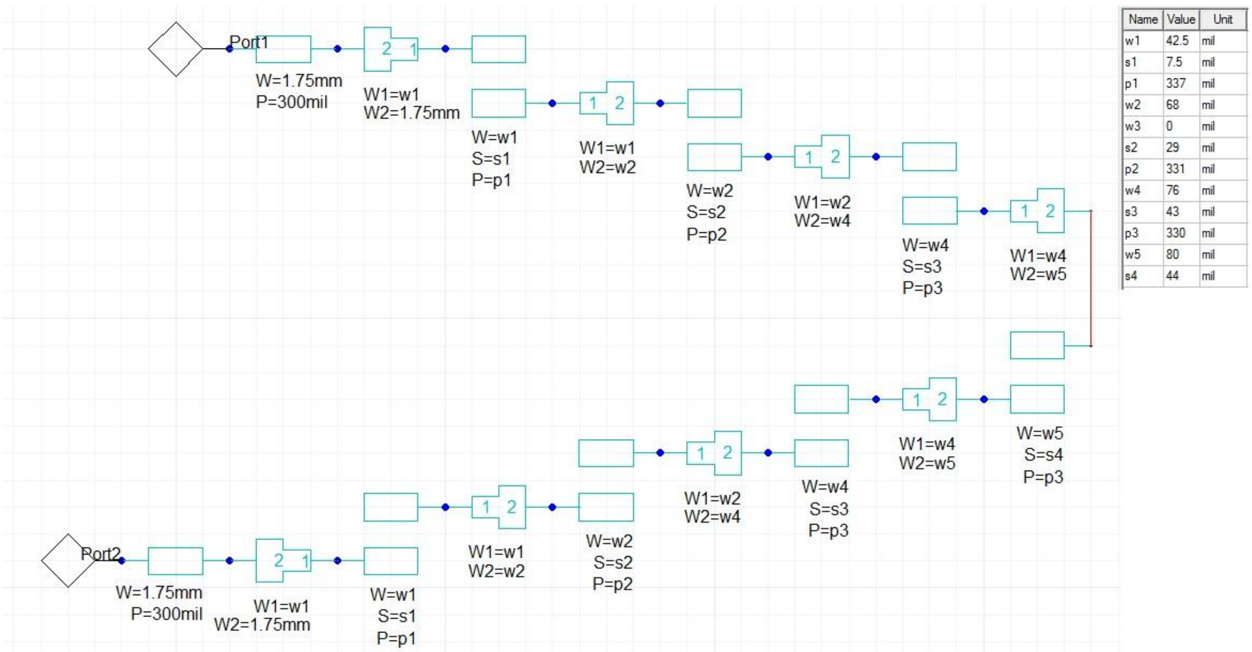

Figure 14: Edge-couple bandpass filter of 6 orders in microstrip.

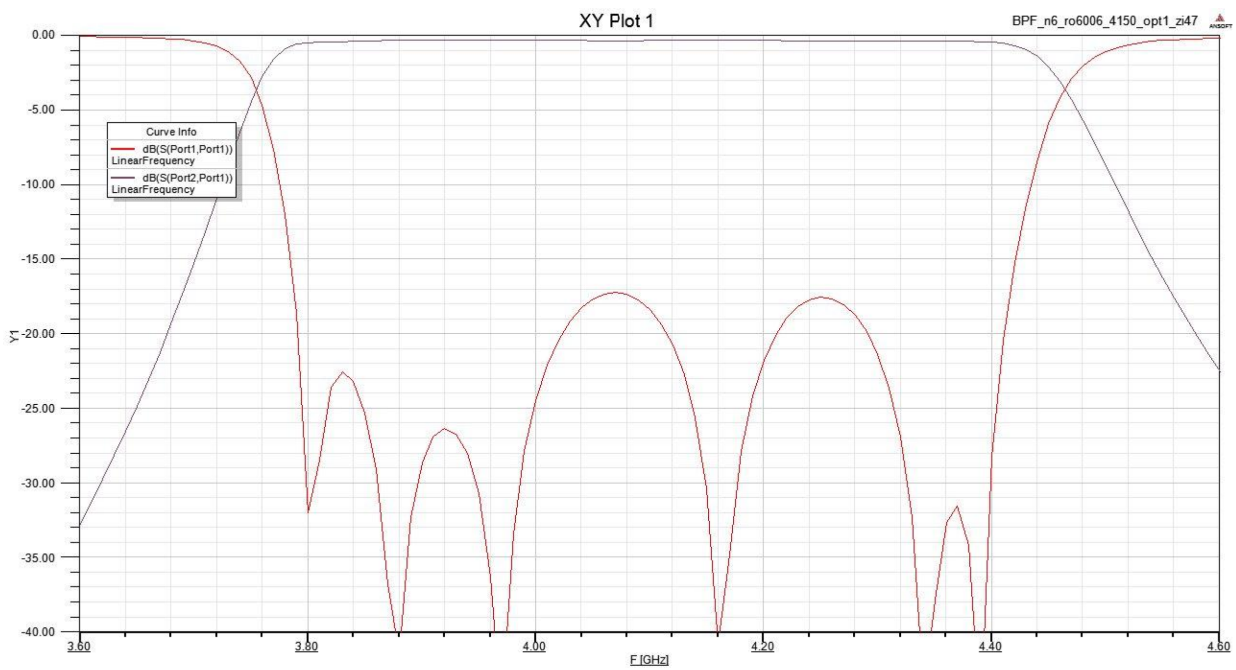

Figure 15: Results of tuning in Designer for a center frequency of 4.1GHz.

Note for the above figure that the S11 of the middle and upper band may seem like a poor result of optimization, but this approach was taken due to the results of the 5-order filter when simulated in

HFSS. The previous results in HFSS show degraded performance in the lower band and excellent performance higher in the band. This result was taken into consideration for the redesign of the filter. The figure below shows a zoomed-in view of the insertion loss in the passband of the optimized 6 order filter.

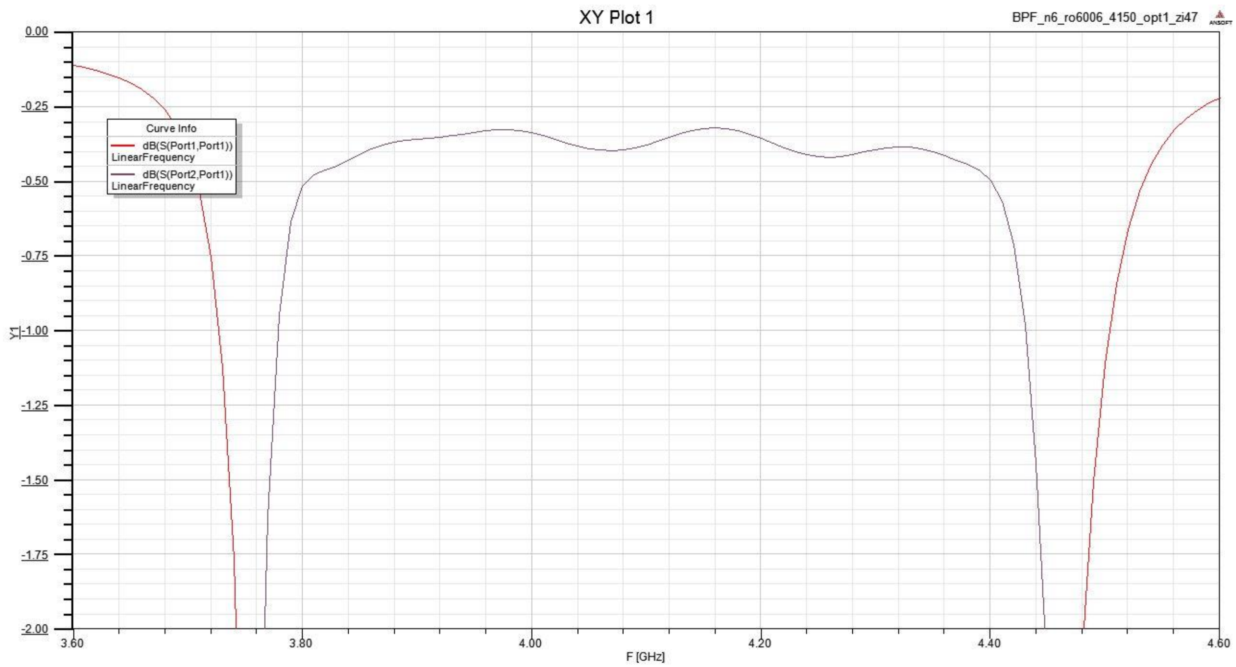

Figure 16: Insertion loss results of the first optimization of the 6 order filter in Designer.

The circuit model is again exported to HFSS as before. A solution is found again at 4GHz and a Fast frequency sweep is performed from 3 to 5 GHz, with a radiation boundary on the air box “top” and “ends”. The model of the circuit and the results are shown below.

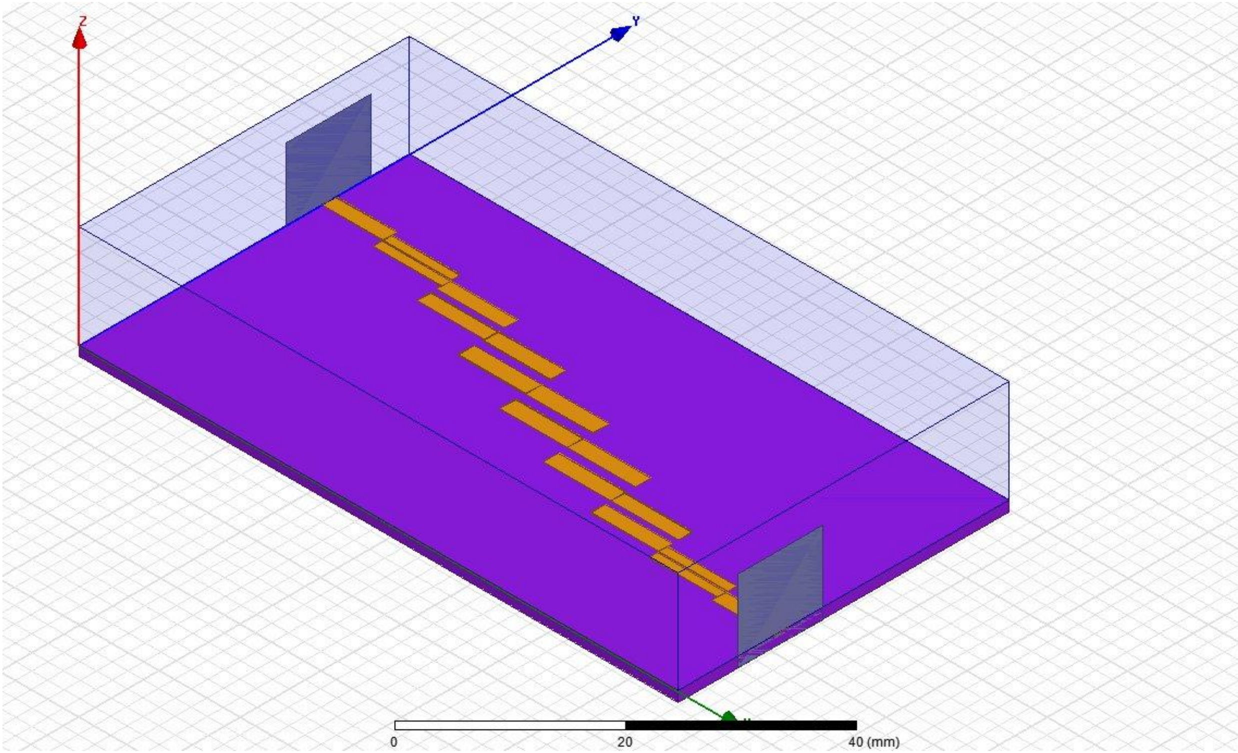

Figure 17: HFSS model of the 6 order filter.

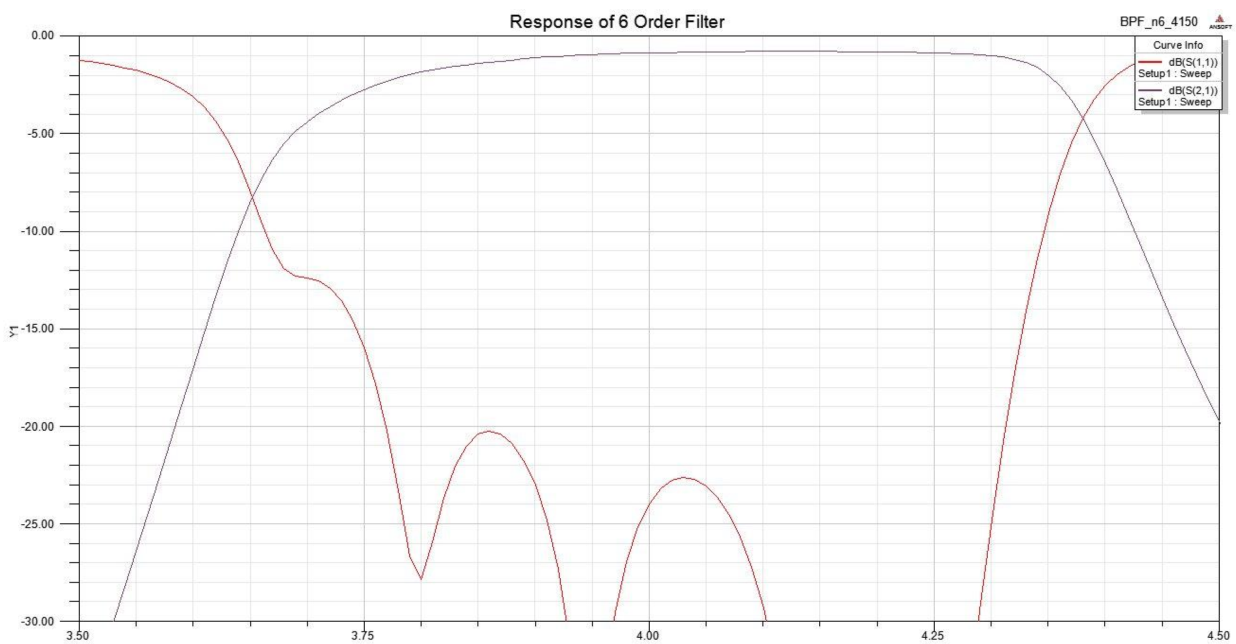

Figure 18: HFSS response of 6 order, first optimization.

As predicted, the simulation in HFSS lowers the passband center frequency by about 100MHz. Similar to the 5-order, the performance of S11 is degraded at the lower end of the passband, whereas the performance is excellent in the higher region. This is the focus of continued optimizations in Designer, in an attempt to have HFSS results predict S11 to be less than -20dB throughout our passband. For a lossless filter, with an insertion loss having a maximum ripple of .05dB, the return loss must be 19dB or higher[1].

The filter is re-optimized in Designer and re-simulated in HFSS until a sufficient results is achieved. The figures below are the result of our final optimization.

Name	Value	Unit
w1	41	mil
s1	7.5	mil
p1	339	mil
w2	68	mil
w3	0	mil
s2	26	mil
p2	331	mil
w4	76	mil
s3	40	mil
p3	331	mil
w5	77	mil
s4	42	mil

Figure 19: Physical dimensions after final optimization in Designer

[1] It is left to the reader to follow through with a proof, if interested.

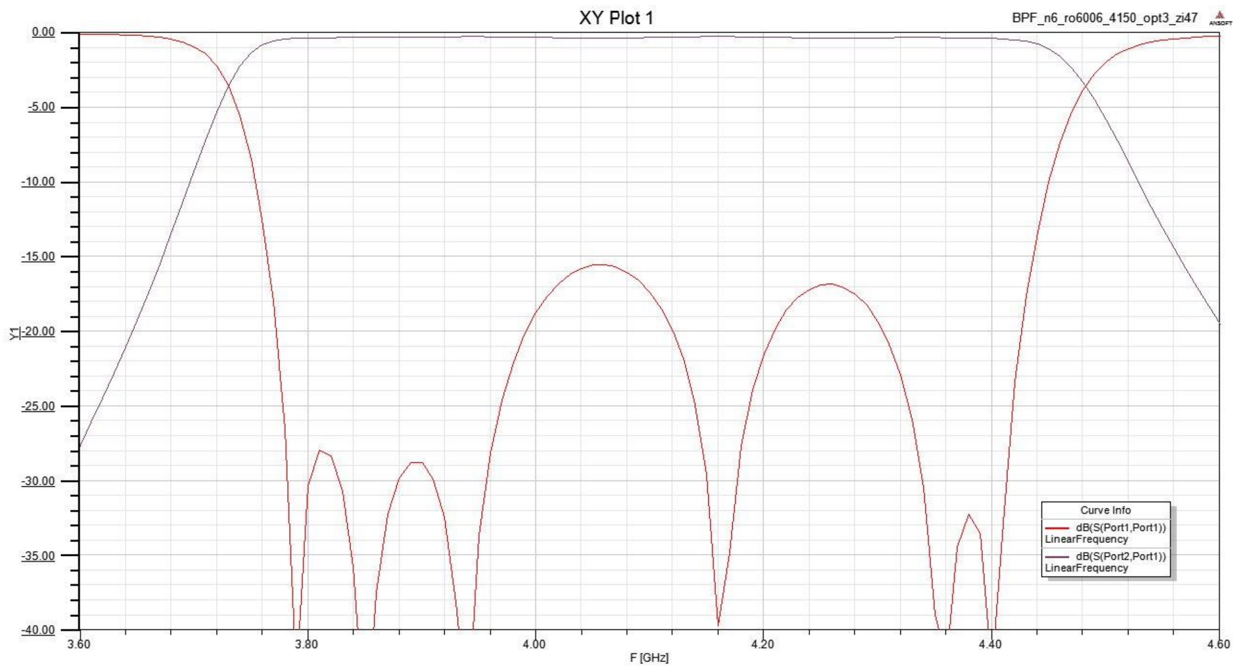

Figure 20: Final optimization in Designer

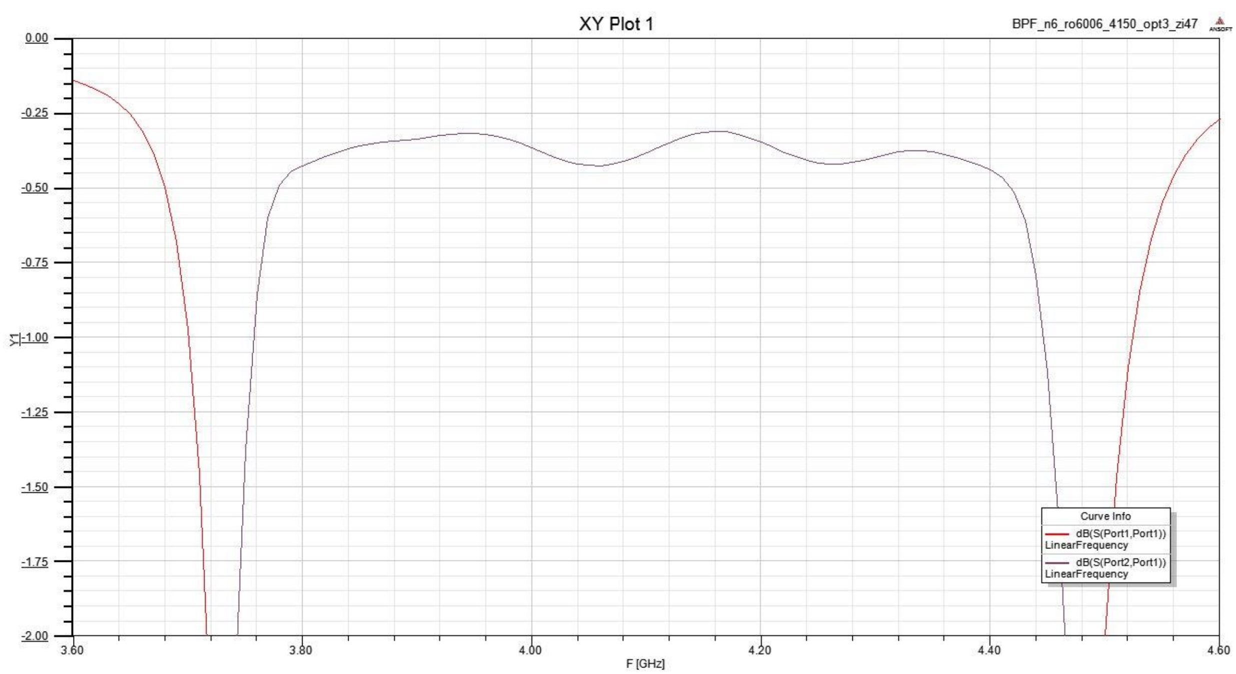

Figure 21: Zoom of final optimization in designer

Results show the upper cutoff is not as sharp as previously, but is very close to meeting spec. Similarly the ripple does not meet spec because as mentioned previously, the return loss is not lower than -19dB. However, the results in HFSS are anticipated to be different.

The circuit model is again imported to HFSS, however the model is optimized to run more smoothly. Initial responses of simulation (not shown) indicated a problem with the geometry of the model within the problem space in the HFSS model. The model is changed so that minimal extraneous objects exist such as extra dielectric, and the model is no longer in a parallelepiped. The design is taken “out of a box” in order to break any box resonances that may be occurring, and to lower the final mesh size by removing air and substrate far from the circuit. Also, the box height was raised to improve results and port height lowered. The port height was lowered such that any further decrease in size would affect the response of input impedance. Radiation boundaries were selected at the top and ends of the model as shown below. Selecting the sides significantly increased the simulation time and produced different results

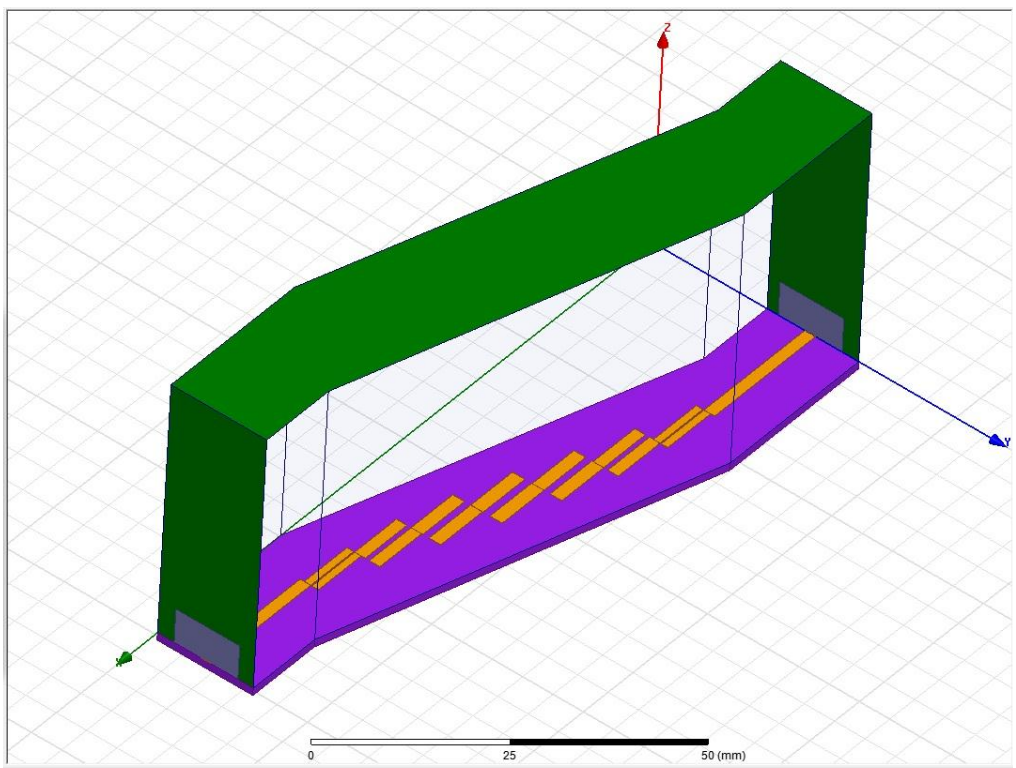

Figure 22: Radiation boundaries are highlighted in green

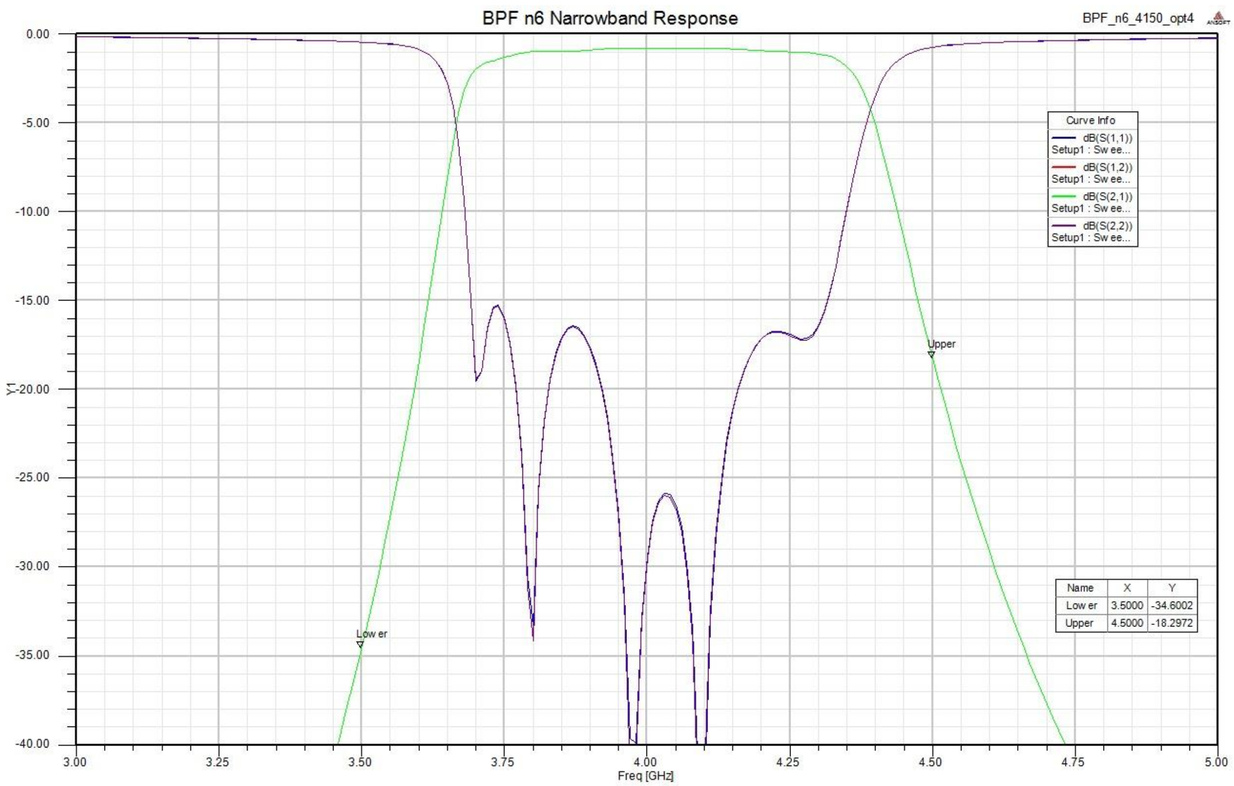

Figure 23: HFSS response after final tuning

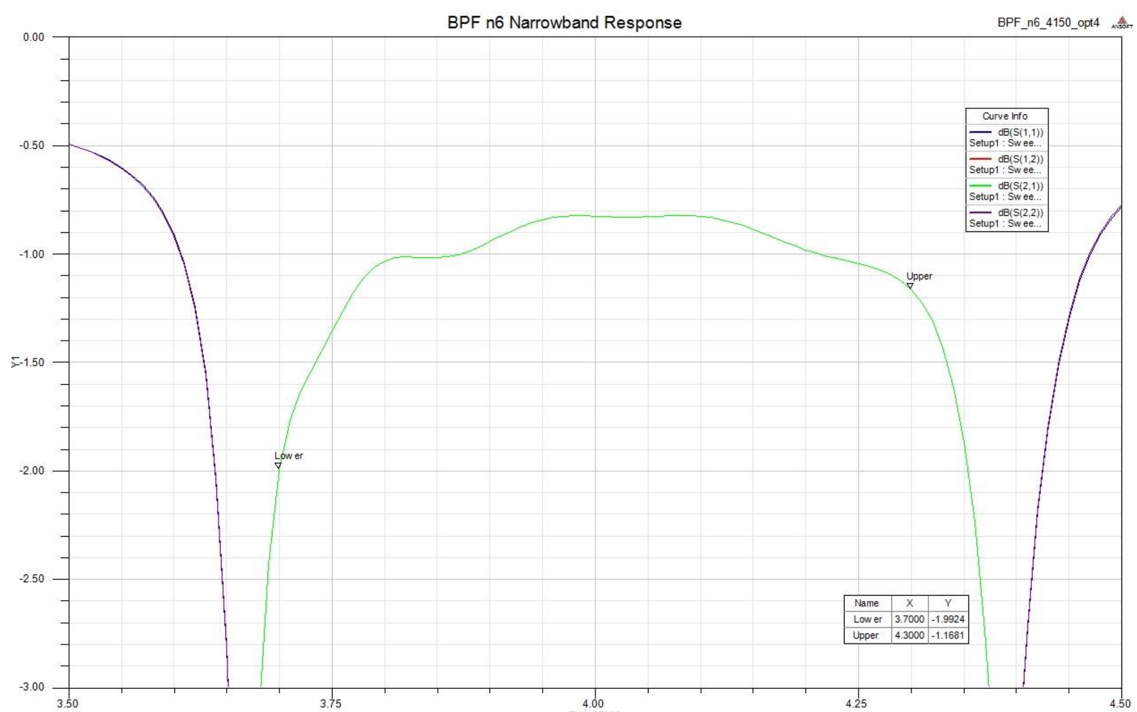

Figure 24: HFSS narrowband results after final tuning

While these final results of HFSS do not fully meet the specifications in the HFSS simulation results, the results are somewhat expected by the design team. The pass-band is very near 4GHz with a 15% bandwidth, depending on the users definition of bandwidth. The chebychev definition is at maximum ripple, with max ripple defined as .05dB. However the bandwidth is 15% with an insertion loss of less than 1.5dB, or a “-1.5dB bandwidth.” The minimum rejection at normalized frequency is close the specification of -20dB with performance around -18dB. It was decided by the design team to present a fabricated and verified filter design at the project deadline, rather than to continue optimization and present results in HFSS showing excellent and in-specification response but with no physical circuit to measure or present.

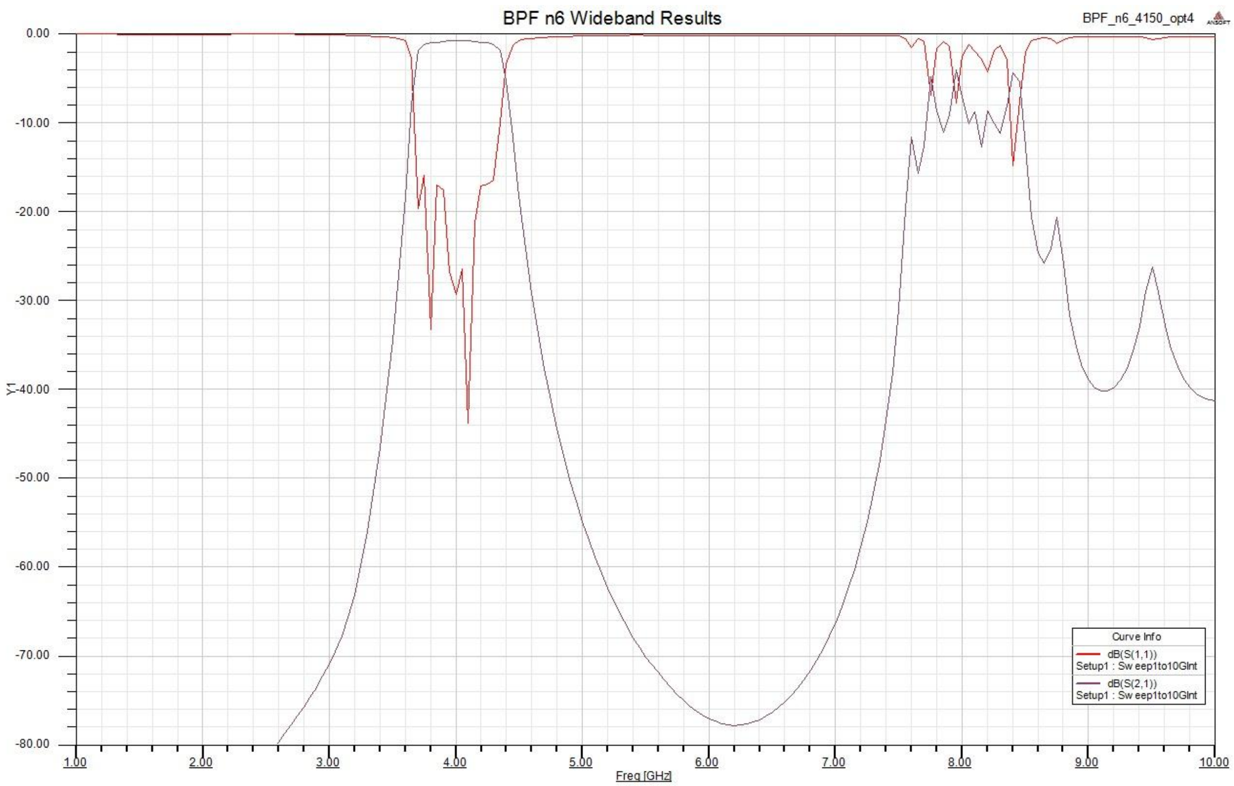

Figure 25: Wideband results

The upper response near 8 GHz is expected. If there were additional time or the requirements to do so, a low pass filter could be incorporated into the design.

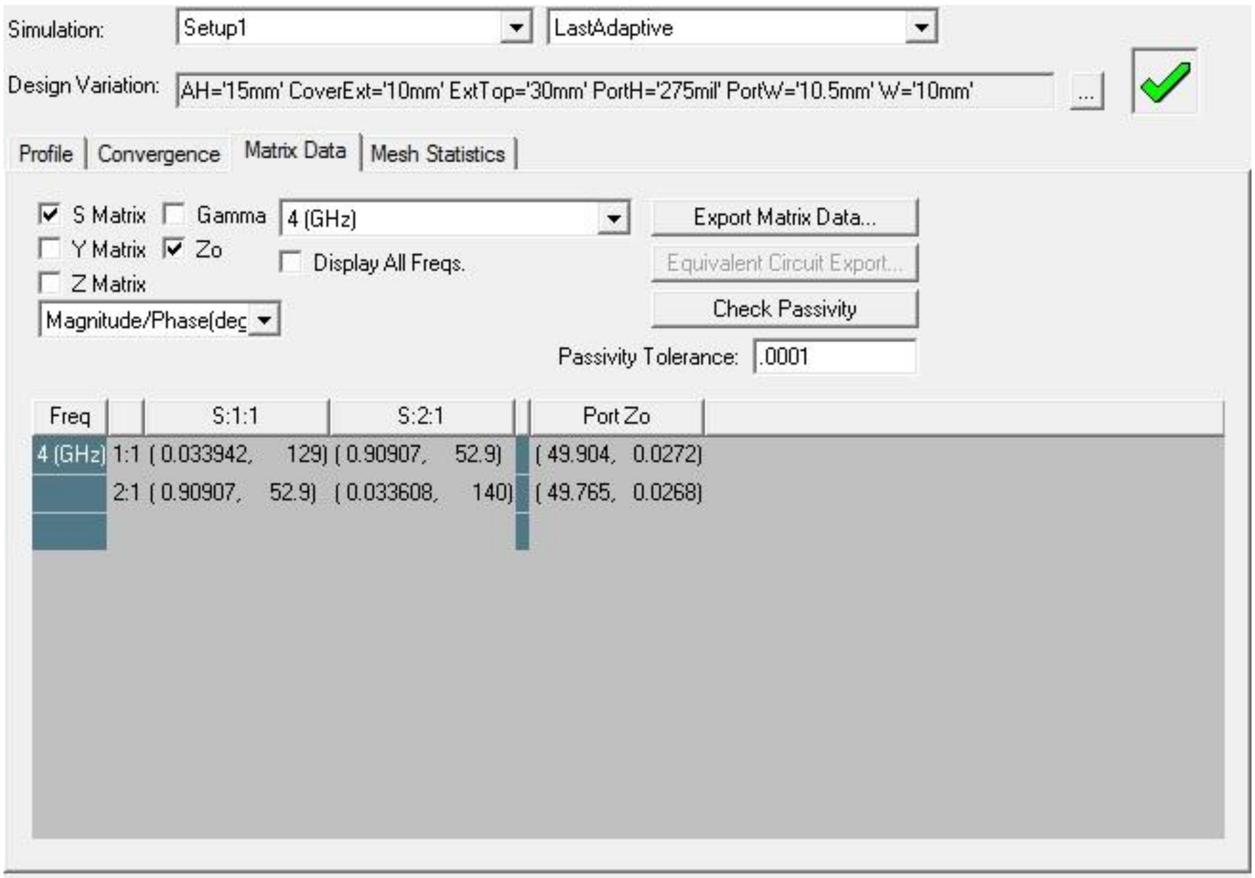

Figure 26: Matrix data showing a very nicely matched Zo (.05% error)

Fabrication

In order to verify the effectiveness of the presented design procedure, the accuracy of the design, and verify the final HFSS simulation, the designed circuit needed to be fabricated and measured. The authors converted the final HFSS model into an AutoCAD [5] compatible DXF file which can be used by the LPKF ProtoMat S62 rapid prototype machine. The design team received assistance from graduate student Andrew Smart to operate the machine.

After fabrication, the authors noticed various issues present in the fabricated version which are circled in the below picture.

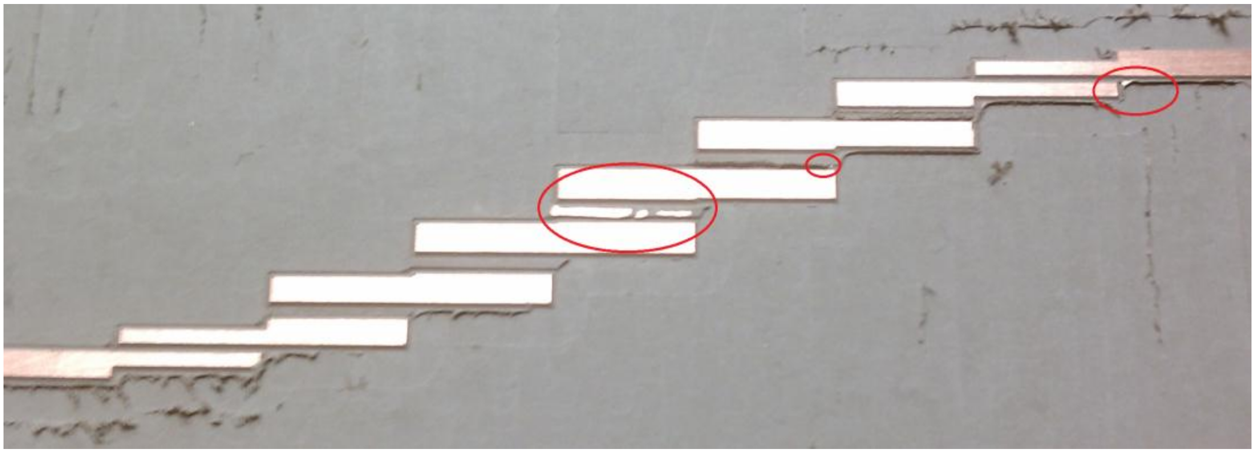

Figure 27: the fabricated circuit had several issues

The offending metal traces were easily removed with an exacto-knife. The authors then proceeded to add two 50 ohm SMA connectors to the ends of the board such that the board may be connected to a network analyzer for measurement. The SMA connectors had to be soldered directly onto the board which introduces minor errors due to changes in conductivity present at the solder joints. The following graphic is a picture of the complete board with the SMA connectors attached.

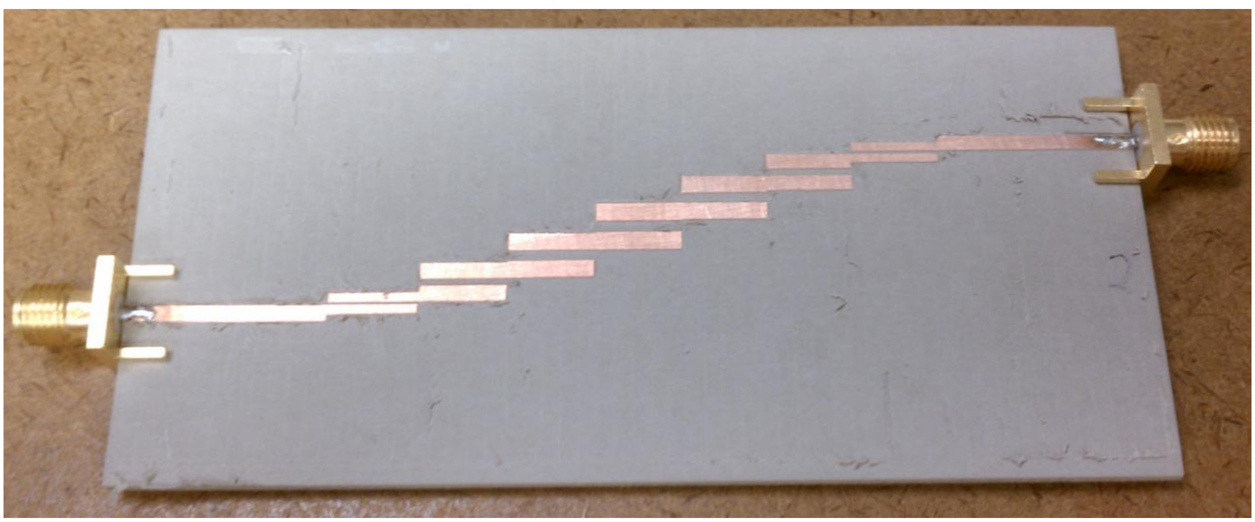

Figure 28: the fabricated circuit with SMA connectors

Measurement Results

In order to verify the accuracy of the final HFSS simulation and the effectiveness of the presented design procedure the fabricated circuit's response would need to be measured. The board's SMA connectors were compatible with the ANSYS E5071C network analyzer.

Before measurement could take place the authors calibrated the network analyzer over the desired measurement frequency ranges. The filter response was measured over two frequency ranges: a wide-band/low-resolution measurement and narrow-band/high-resolution measurement. The purpose of two measurements is that it is beneficial to have an understanding of the response of the filter outside of our pass-band. This includes knowledge of any harmonics present at higher frequencies. The wide-band measurement was performed between 100 KHz and 8.5 GHz; this is the full simulation range of the network analyzer. The authors also performed a fine tuned measurement which gives a high resolution measurement detail for the main region of operation. The narrow-band measurement was between 3-5 GHz with 801 points. The network analyzer was calibrated in both cases with an electric calibration kit.

The following diagram shows the wide-band measurement of the fabricated edge coupled filter.

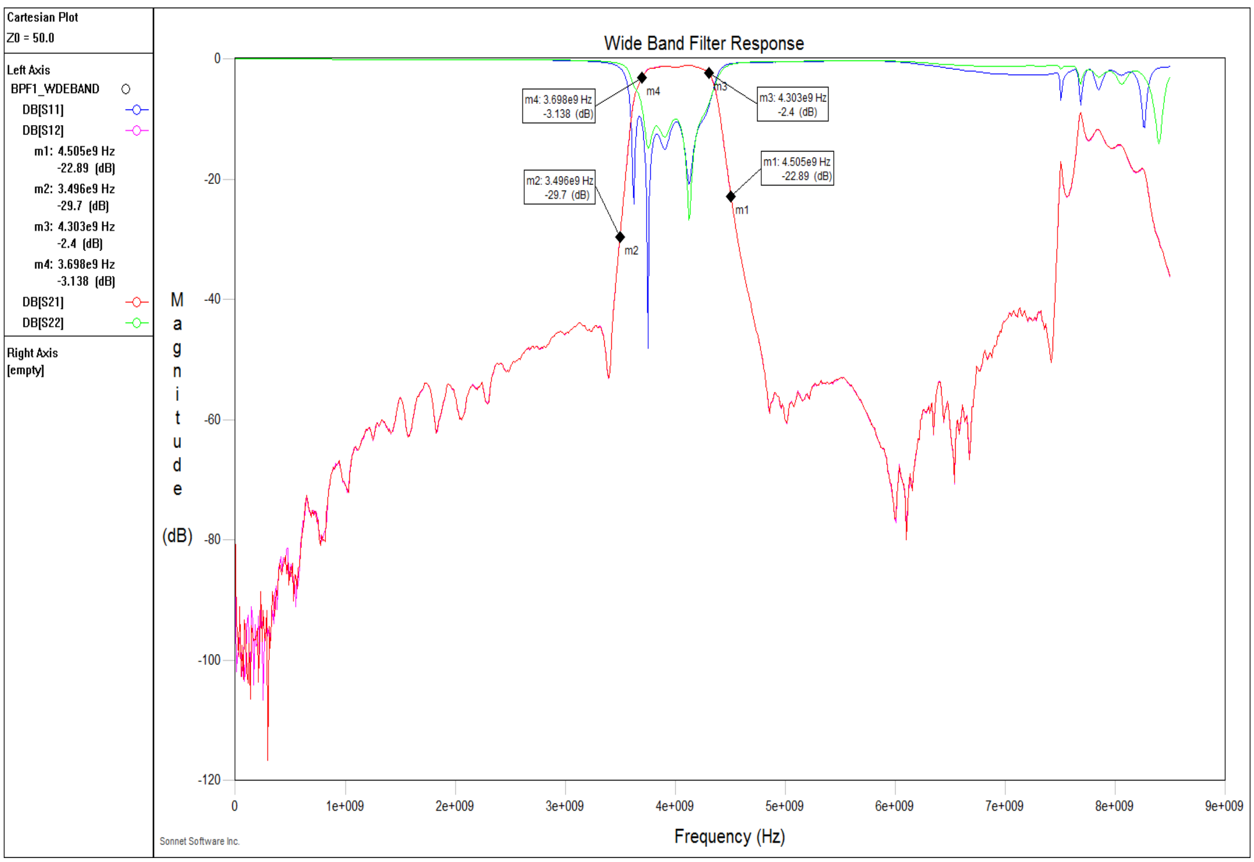

Figure 29: Wide-band filter response from measurement

The wide-band frequency response shows a second harmonic present at 8.1 GHz. Ideally the band-pass filter would be combined with a low-pass filter to subdue the harmonic response.

The following diagram shows the narrow-band frequency response for the filter compared to the results obtained from HFSS. The HFSS return loss and insetion loss (S11 and S21, respectively) results are shown as dotted lines in the picture; the measured S11 and S21 responses are shown as solid lines.

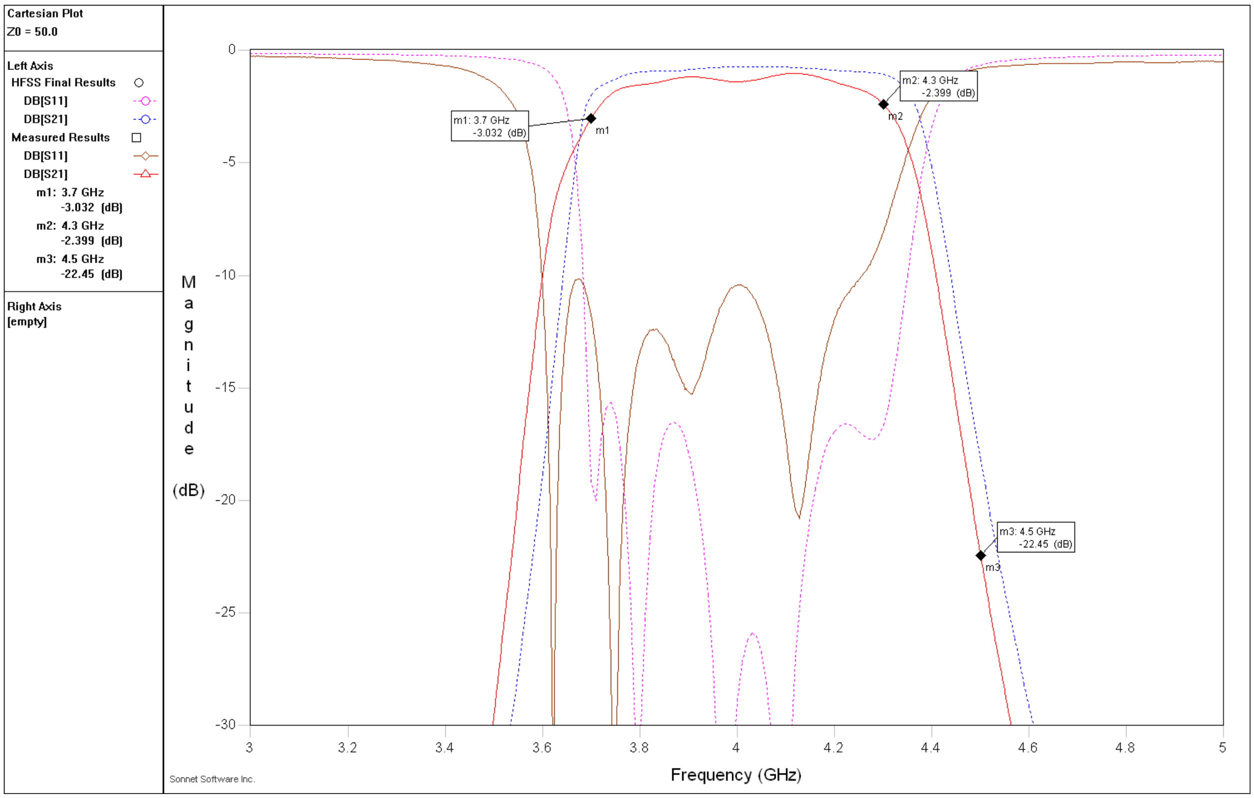

Figure 30: Narrow-band filter response comparison between HFSS and measurement

The narrow-band response plot shows that the S21 response of our filter was approximately 1 dB lower in the pass-band than the HFSS simulation. The measured center frequency is very closely centered at 4 GHz; the HFSS simulation is shifted to the right by approximately 50 MHz. The HFSS results cut-off more sharply and the lower end of the pass-band but the two responses cut-off equally well on the higher end of the pass-band. The measured S11 response cuts-off at a frequency of 3.45 GHz compared to the HFSS simulation which cuts-off at 3.5 GHz on the left side of the pass-band.

The authors are very confident in the accuracy of the HFSS simulation; the authors attribute observed errors to inconsistencies with the fabricated board. Error can be attributed to the fabrication tolerance of +/- 0.5 mil imposed by the cutting instrument. The LPFK machine will remove a small amount of the dielectric material when fabricating the board which affects the height of the substrate. There are also tolerances present in the Rogers 6006 substrate specification: the substrate datasheet indicates that although the expected dielectric constant is 6.15 they have measured their produced boards to a dielectric constant of 6.45. The authors’ soldering ability is also a source of error; the solder joints placed on the filter feed-lines introduce an amount of back reflection and loss to the circuit. Overall the measured result matches fairly reasonably with the full wave simulation.

Conclusion

An effective general procedure that may be applied to the design of many RF circuit designs has been reviewed. The authors utilized the proposed procedure in an effort to design an edge coupled band-pass filter centered at 4 GHz with a 15% bandwidth based on Chebyshev approximation. The report outlines the challenges present in the translation between low complexity circuit models to higher complexity physical models, and provides an in-depth analysis into the causes of such discrepancies. The final fabricated circuit board's response was compared to the full wave simulation results to assess the effects of physical manufacturing on circuit response. Although the fabricated results do not match exactly with simulation results the authors agree that the errors are not overly extensive and the presented process may be considered a success.

References

[1] *MATLAB*. Vers. 2011b. Natick, MA: MathWorks, 2011. Computer software.

[2] *Ansoft Designer*. Vers. 6. Pittsburgh, PA: Ansoft Corp., 2011. Computer software.

[3] *Ansoft HFSS*. Vers. 13. Pittsburgh, PA: Ansoft Corp., 2011. Computer software.

[4] Sabbagh, Mahmoud. Microwave Labratory Experiments: Experiment 3, Microwave Filters. Syracuse, NY: 2011.

[5] Bartels, Jeff. *AutoCAD 2011*. Vers. 18.2. Ventura, CA: Lynda.com, 2011. Computer software.

[6] *Sonnet Suites*. Vers. 13. Syracuse, NY: Sonnet Software Corp., 2011. Computer software.