Ladder Filter Design, Fabrication, and Measurement

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February 18, 2016

1   Introduction

Read the introductory material in the "Lab 3 Background Reading" document.

2   Prelab

1. Design an LC low-pass ladder filter to meet specifications.

   (a) Design an LC low-pass ladder filter with a bandwidth of 100 MHz, in-band ripple of 1 dB, with 40 dB of attenuation at 200 MHz. Determine the required filter order and the component values for the filter. The filter should be designed to interface to a 50Ω environment. You may use filter tables, software tools, or internet based tools to design the filter. Make sure that the filter component values are realizable (in an 0603 footprint) and not unreasonably small ($L < 0.5$nH or $C < .1$pF) or large ($L > 400$nH or $C > 1$nF).

   (b) Simulate your filter in SPICE (ADS or SpectreRF) and verify the performance. Include plots of the magnitude and phase response on a log-scale. Identify the bandwidth, stop-band rejection and the in-band ripple.

   (c) (*Optional*) Simulate your filter using "Monte-Carlo" analysis by varying the components by 20%. Depending on the simulator, you can do this by specifying each component to be a random variable with the given mean value and standard deviation (assuming Gaussian). The simulator will then run several hundred iterations of the simulations while varying the component values according to the given statistics. Comment.

   (d) Simulate the filter response but include the effect of finite component Q. Assume that inductors with Q = 20 and capacitors with Q = 100 are available. How does the component Q impact the filter response?

2. Design an LC band-pass ladder filter to meet specifications.

   (a) Design an LC band-pass ladder filter with passband from 630 MHz to 780 MHz, in-band ripple of 1 dB. Use the minimum filter order possible to realize a stop-band rejection of 25 dB at 550 MHz.

   (b) Simulate your filter in SPICE (ADS or SpectreRF) and verify the performance. Include plots of the magnitude and phase response on a log-scale. Identify the bandwidth, stop-band rejection and the in-band ripple.

   (c) (*Optional*) Simulate your filter using Monte-Carlo analysis by varying the components by 20%. Comment.

   (d) Simulate the filter response but include the effect of finite component Q. Assume that inductors with Q = 20 and capacitors with Q = 100 are available. How does the component Q impact the filter response?
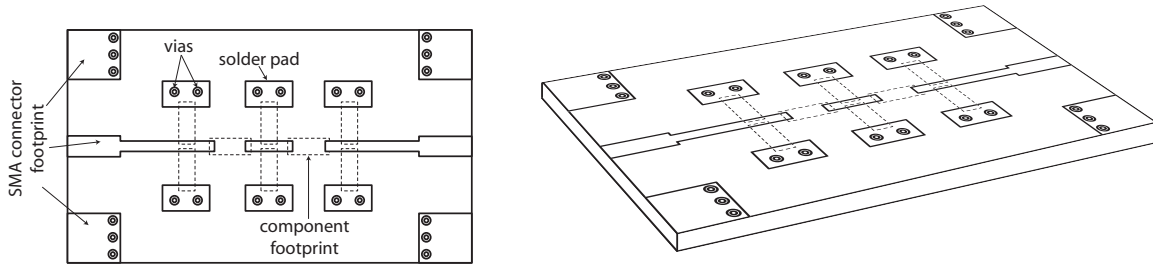
Figure 1: The printed circuit board layout for a ladder filter structure.

Figure 2: (a) An unfinished and (b) finished PCB layout.

3 Experimental Work

3.1 PCB Manufacturing

All circuits will be fabricated using a simple two-layer printed circuit board (PCB). The PCB consists of a dielectric material, usually FR4 ($\epsilon_r = 4.4$), with a thickness of 62 mils, and two layers of Cu metal layer. The metal layers have a thickness of 34 μm. Normally you would pattern the metal layers to produce your circuit but in the interest of time, the boards have been prefabricated to take on a standard form. The backside of the board is a solid ground plane. Connections to ground must travel through a "via" to reach the backside.

For this lab, the layout of the board is shown in Fig.1. The input and output of the board have footprints for SMA connectors which allow you to connect SMA cables. The input and output microstrip transmission lines are interrupted periodically which allows you to place components in series or in shunt in a ladder filter structure. Landing pads with vias to ground also appear periodically to allow shunt components to be soldered to ground.

To solder components onto the board, use standard 0603 components[1] in series or in shunt. The soldering tips PDF on the course website has some helpful info.

3.2 Procedure: Low-Pass Filter

1. Build low-pass LC filter using the provided PCB. The board layout, shown in Fig. 2, supports a ladder filter structure. Note that each series pad can support two parallel

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[1]Components are classified according to their footprint size in mils.

components. Components can be soldered to ground on either side of the board (the top or bottom).

   (a) Verify that your filter topology is compatible with that of the filter PCB. If not, select an alternate topology.

   (b) Simulate your filter design with component values rounded to the nearest value available in lab.

   (c) Simulate your filter design with component parasistics included, corresponding to the selected filter topology. Use your estimated component parasitics from Lab 2.

2. Using the Network Analyzer, measure the magnitude and phase response of the filter. Adjust the start-stop frequencies and the resolution to clearly capture the filter response on a log scale. You should ensure that the input leads of the SMA have been de-embedded from the measurement by recalling the appropriate saved settings on the analyzer. Save the measured S_{11} (input reflection) and S_{21} (transmission) of the filter as an 'S2P' file.

3. The following steps can be done in post-processing, but before doing so you should check that your measured filter response looks similar to what you expect based on simulations.

   (a) Calculate the filter voltage transfer characteristic V_2/V_1 and explain how this is related to S_{21}.

   (b) Compute $1 - |S_{21}|^2$ and compare it to $|S_{11}|^2$ as a measure of the "excess" loss in the filter. Where is the excess loss the greatest?

   (c) Calculate the group delay for the filter in the passband and a few octaves beyond the passband.

   (d) Comment on the accuracy of your design. Also calculate the insertion loss and input impedance of the filter in the pass-band.

4. *(Optional)* Measure the time-domain step response of the filter on an oscilloscope. Save a plot of the step response.

3.3   Procedure: Band-Pass Filter

1. Build the LC band-pass filter using the same procedure as above.

2. Repeat all the measurements on the passband filter. If the measured performance is very different from what you expected, then you have not properly modeled the parasitics of the components. Pay close attention to the component parasitics measured in the first lab.

3. *(Optional)* If time permits, build an LC band-pass filter using a board with wide or narrow traces.

4 Post Laboratory

1. Compare measurement and simulation results by overlapping the measured S_{11} and S_{21} of your filter with the simulations. Explain differences.

2. In the design of a communication system, which filter non-ideality would you consider to be the most important? Explain.

3. Modify schematic to match measurements. You should use your knowledge of the board level parasitics and component non-idealities. If you did not measure the components and the board, the GSI can provide you the appropriate data. Make sure you understand the various measurements of the board level parasitics. The component models can also be obtained from the manufacturer.

4. Consider different board layouts employing either wider or narrower traces. Explain how each layout should affect the overall response of the filter. *Optional*: Do measurement results confirm your intuition.

5. How much time did you spend on this lab? Any feedback is appreciated.

5 Lab Report

This section is meant to provide a guide for the expectations in the lab report. The goal is not to create a gigantic document with pages and pages of graphs, but to concisely show your results from the lab and explain any deviations from expected results.

5.1 Lab Report Rubric

Although your filters should be designed to meet the specifications in the lab report, it is not worth spending 40 hours in lab soldering and de-soldering components to make sure your measured filter response works similarly.

25%	Pre-lab (filter designs)
20%	Low-pass measurements
20%	High-pass measurements
10%	Discuss differences between sim and meas.
5%	Meeting specifications

5.2 Length

Presenatation is key in technical reports, and a concise but well written report is far easier to read than one with many plots scattered across tens of pages. Please try to keep the reports under 10 pages if possible. If you are having trouble meeting this limit, smaller figures and/or the use of subfigures can help reduce the amount of space taken up by graphics.

6   References

I found the following references useful in reviewing material for this lab. There is a good lecture on filters in EECS 247 [4]. Hagen's book [5] has a nice and easy chapter on filters. The website http://www-users.cs.york.ac.uk/ fisher/lcfilter/ uses the design procedure from Hagen for generating standard ladder filters. The definite reference for filter tables is the handbook by Matthaie and co-authors [2]. Many other online tools exists for commercial programs such as MathCAD, Mathematica, and matlab, in addition to stand-alone programs. Check online and for links in the *RFCafe* website. You can also use the filter synthesis package that comes with the ADS program. For background reading I used Wikipedia [6], which is a valuable and evolving source of information. To learn how to design higher frequency filters and distributed element filters using the insertion loss method, consult a book on Microwave Circuits such as Pozar [7]. If you are interested in the deep theory behind filters, read a book such as *Network Theory and Filter Design* [1].

References

[1] V. K. Aatre, *Network Theory and Filter Design*, 1986, New Age Publishers.

[2] G. Matthaei, L. Young, *Microwave Filters, Impedance-Matching Networks, and Coupling Structures*, 1980, Artech House.

[3] *wikipedia.org*, "Chebyshev filter".

[4] B. Boser,*EECS 247 Lecture Notes*, University of California, Berkeley.

[5] J. Hagen, *Radio-Frequency Electronics: Circuits and Applications*, 1996, Cambridge University Press.

[6] *wikipedia.org*, "Electronic filter".

[7] D. Pozar, *Microwave Engineering*, 1998, Wiley.