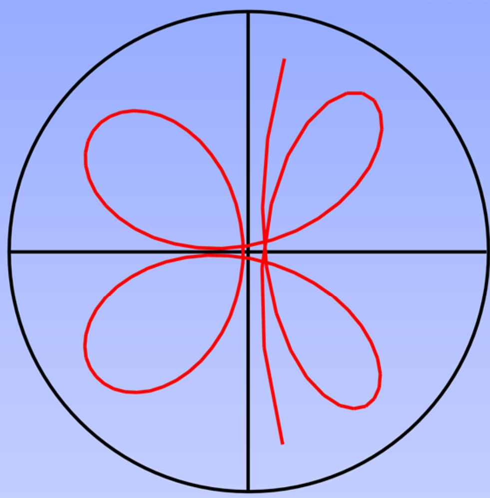
Microstrip Cross-Coupled Filter Design With Sonnet **em**



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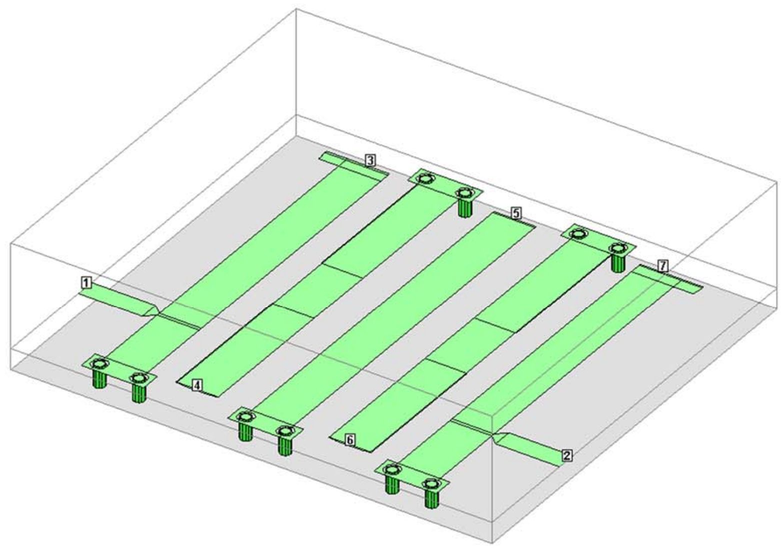
Today I would like to present a short introduction to microstrip cross-coupled filter design. I will be using Sonnet **em** to analyze my planar circuit. And I will be using our optimizer, EQR_OPT_MWO, in conjunction with NI AWR Microwave Office to port tune the EM simulations. I would like to thank Brian Rautio and Sonnet Software for sponsoring this webinar.

Narrowband Interdigital Filters

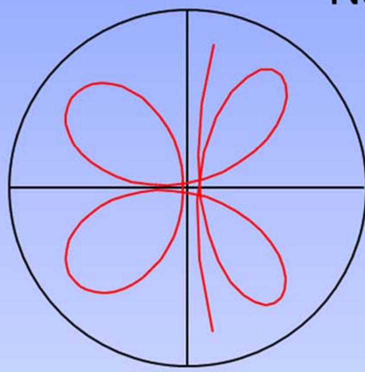


D. G. Swanson, Jr., “Narrow-Band Microwave Filter Design,” *IEEE Microwave Magazine*, vol. 8, no. 5, pp. 105-114, Oct. 2007.

Cross-Coupled Filter Design 2

In 2007 I published this tutorial the design of microstrip interdigital filters.

Narrowband Combline Filters



Narrowband Microstrip Filter Design With NI AWR Microwave Office
June 24, 2015

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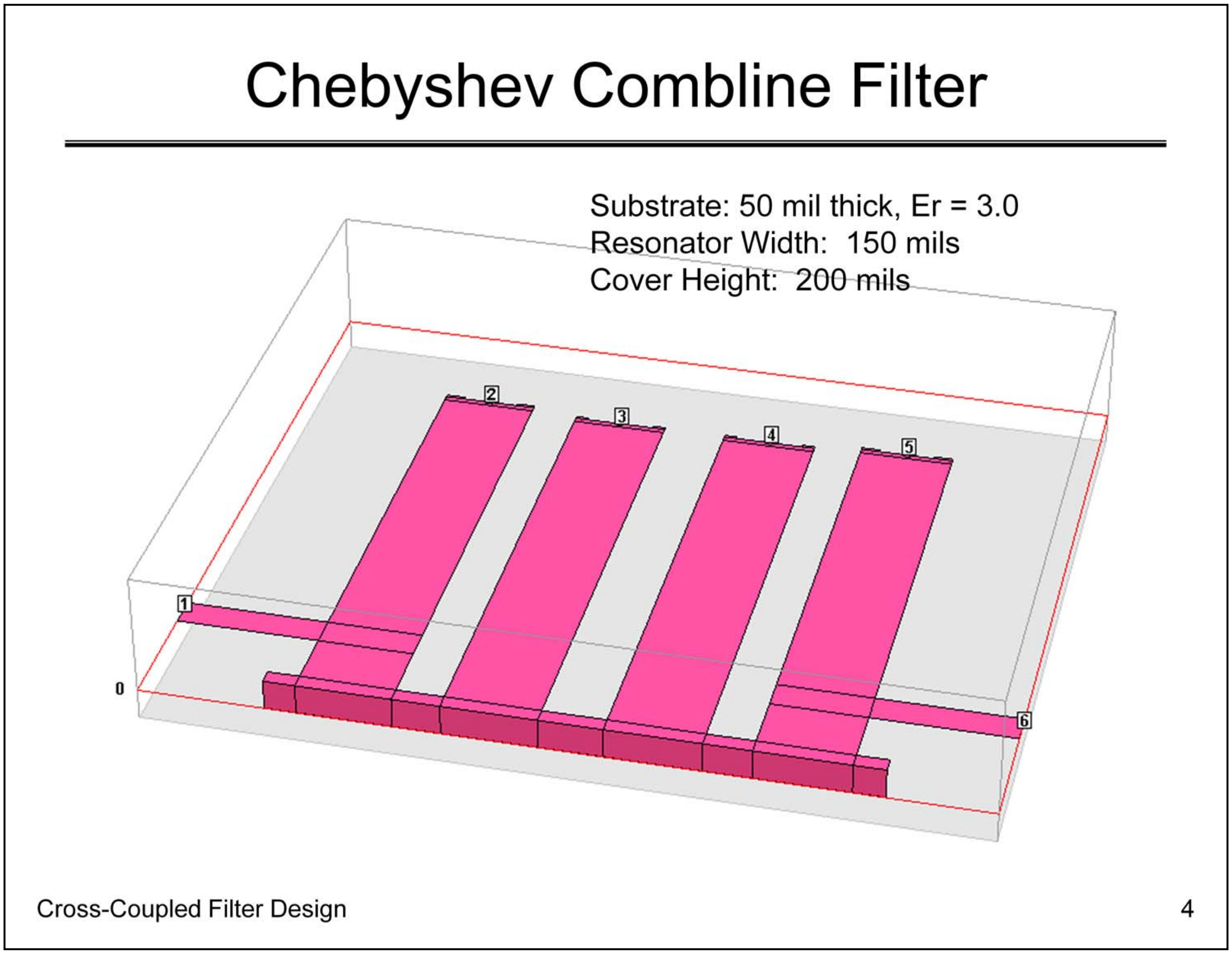
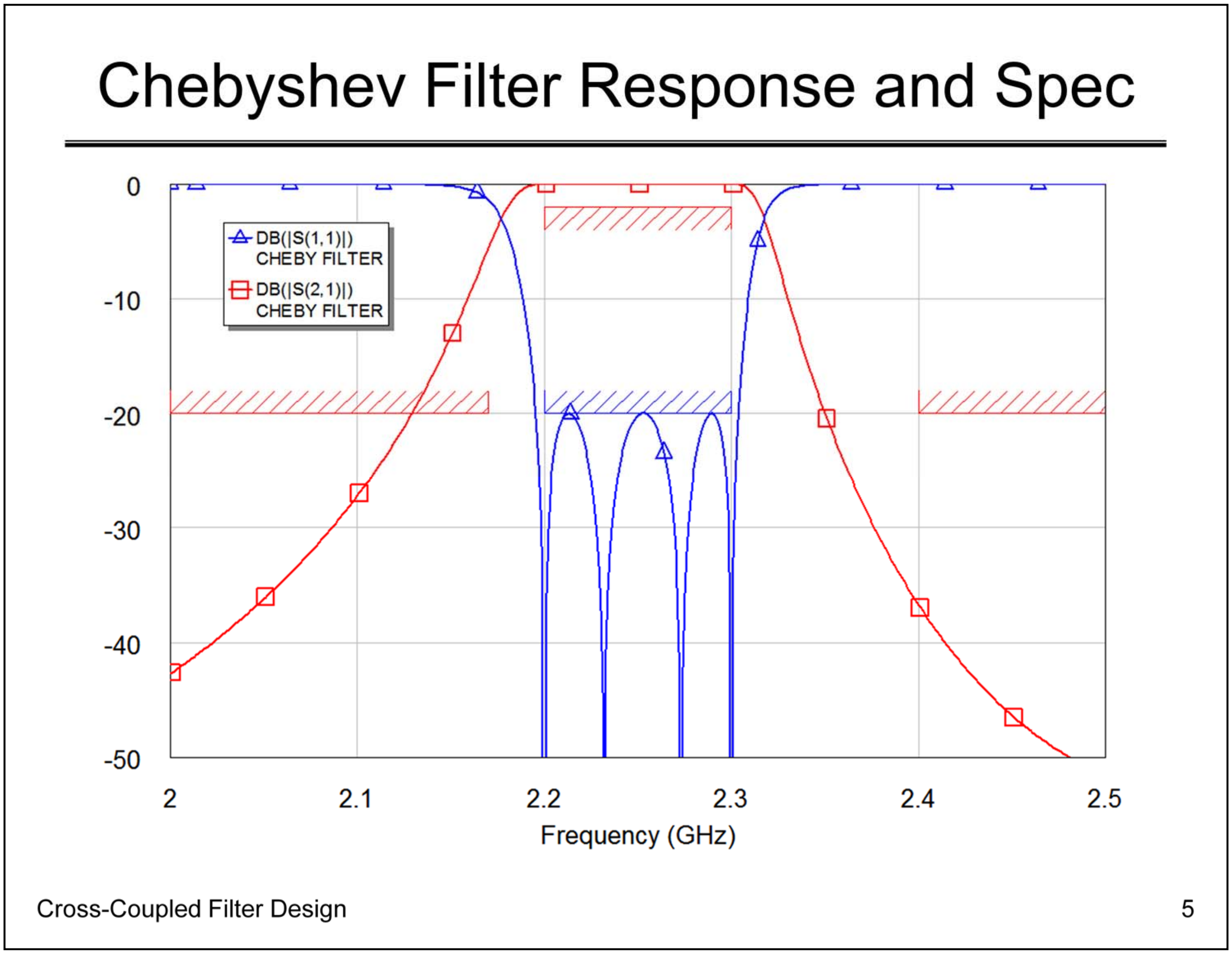
Video available at www.microwavejournal.com

Cross-Coupled Filter Design 3

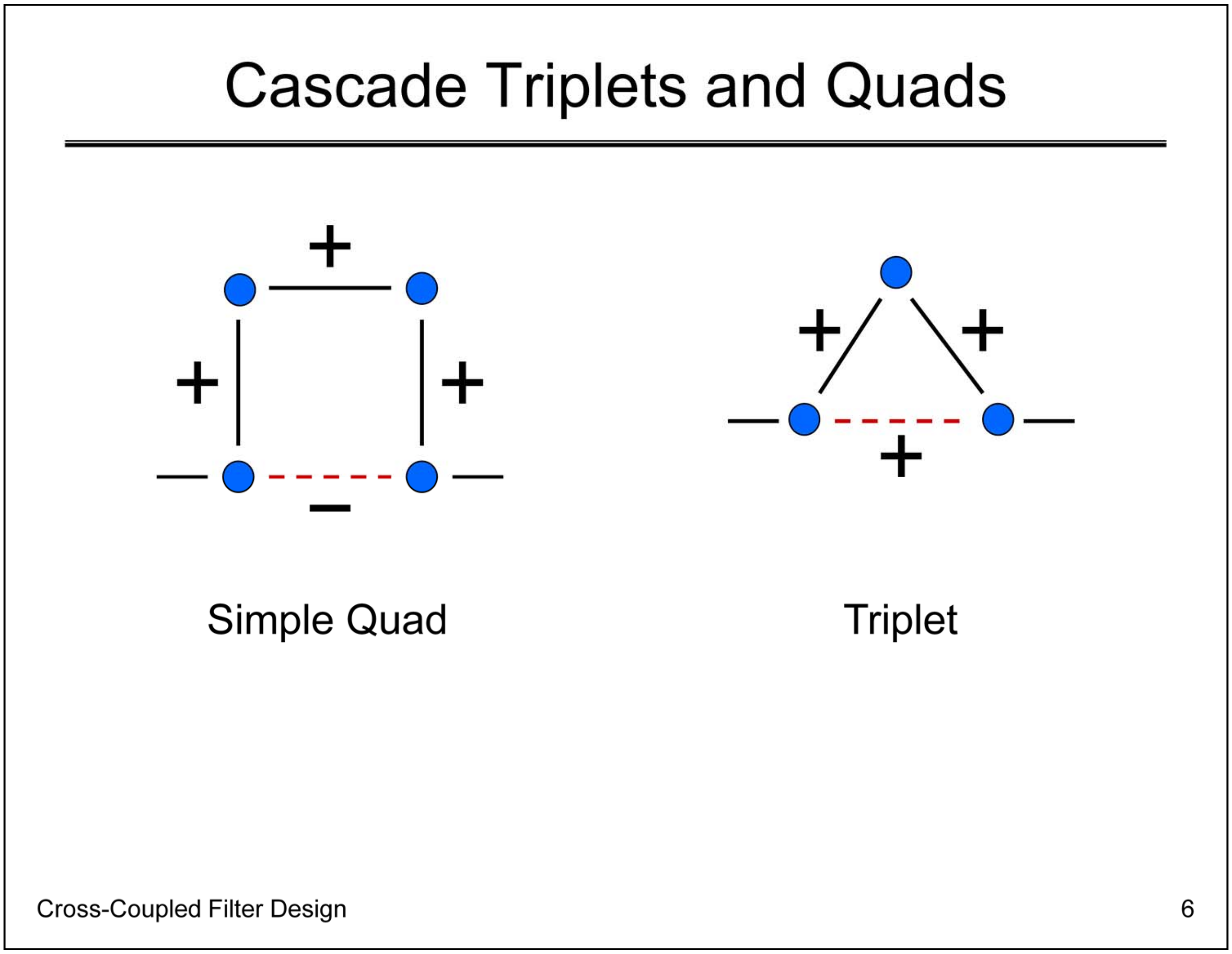
In 2015 I presented this webinar on the design of microstrip combline filters. You can find the slides on the DGS Associates web site and the video is archived on the Microwave Journal web site. Today I would like to build on this presentation and create a microstrip cross-coupled filter.



Here is an N=4 microstrip combline filter designed using the techniques in the previous webinar. We are using a thick substrate and wide resonators to maximize the unloaded Q. The filter covers 2.2 to 2.3 GHz and is for an LTE basestation application. It is designed to be a surface mount component on the main printed circuit board. The input and output lines are not 50 ohms, on this thick substrate they would be quite wide. But the tapped combline topology is quite flexible and can accommodate the higher impedance tap lines. The via metal at the base of the filter approximates the plated slot we will use in the final layout.

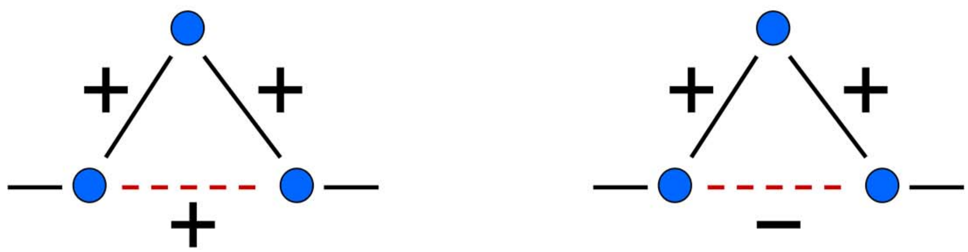


Here is the response of the Chebyshev filter and the specification we are trying to achieve. In the S21 response we find the typical skewing that we see in combline filters: the response is sharper on the high side of the passband compared to the low side. To meet the low side rejection spec we could simply increase the filter order, but the insertion loss would be quite high. Instead, we'll create a transmission zero in the lower stopband to meet the rejection specification.



Let’s do a quick review of cross-coupled filter design. One of the simpler design approaches is to use cascaded triplets and quads. The quad concept starts with four resonators and adds an extra coupling between the first and last resonators. If the coupling is negative with respect to the mainline couplings, a pair of finite frequency transmission zeros will be introduced. In a cavity combline filter, the negative coupling would be a capacitive probe. The triplet concept is very similar and adds an extra coupling between the first and third resonators. In this case a same sign coupling will introduce a single finite frequency transmission zero on the high side of the passband. The concept of triplets and quads dates back to the early 1960’s.

Cascade Triplets

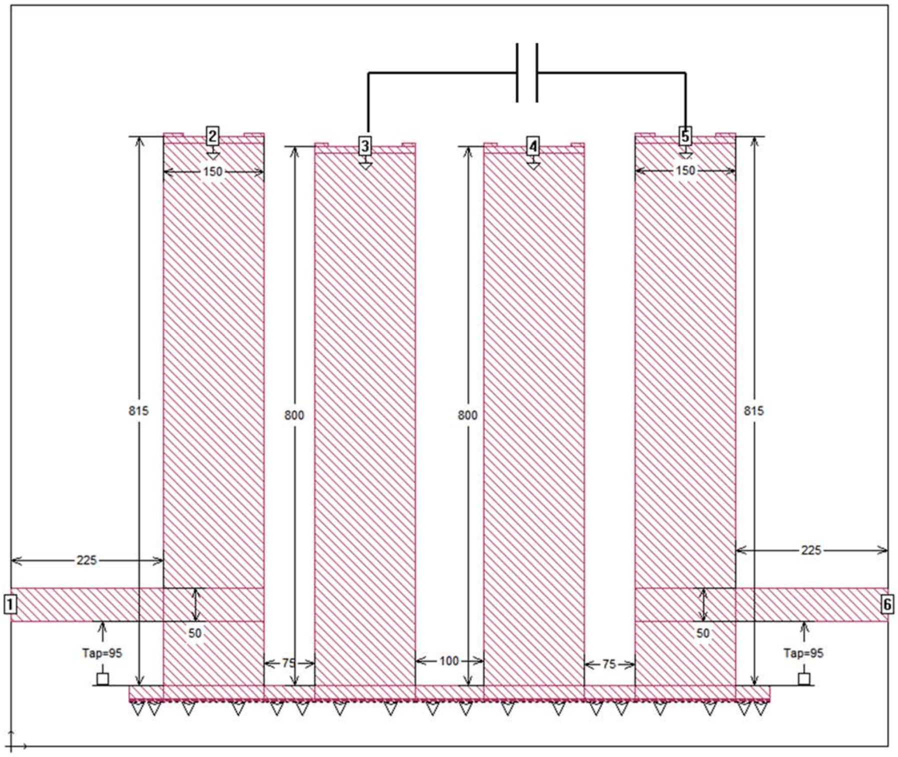


- Pos cross-coupling
- Zero only in upper stopband

- Neg cross-coupling
- Zero only in lower stopband

In the cascade triplet, a negative cross-coupling between the first and third resonators will produce a transmission zero in the lower stopband. And again, for combline filters, we know this coupling wants to be capacitive.

Add Lumped Cap to Chebyshev Filter



Cross-Coupled Filter Design 8

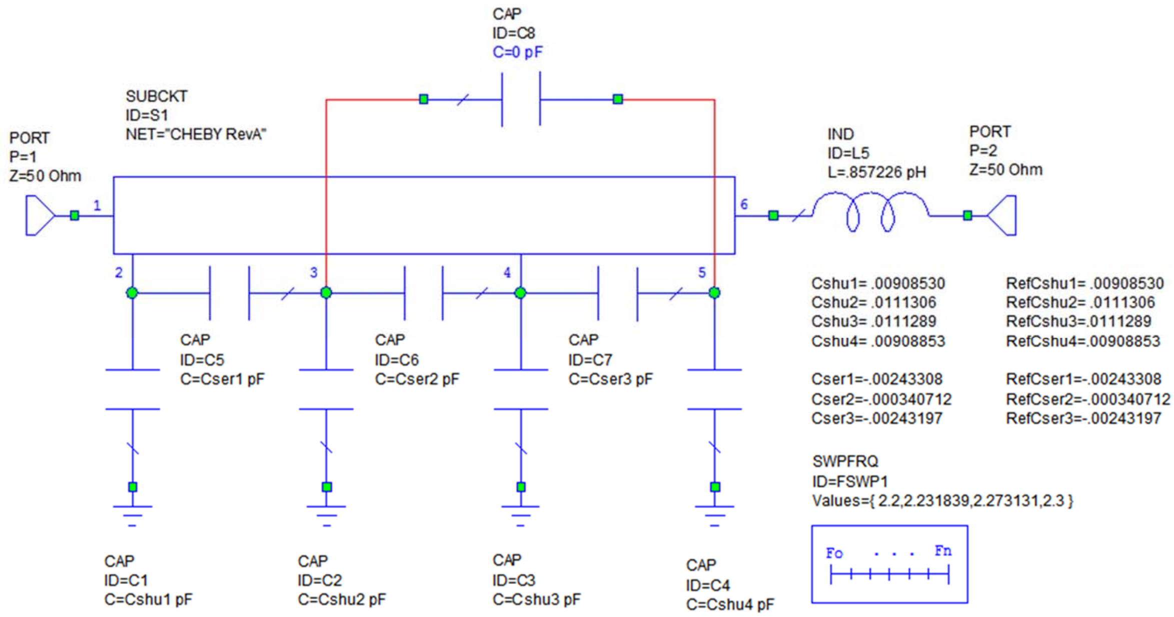
So here is the model of our Chebyshev combline filter in Sonnet **em**. We have added ports at the ends of each resonator so we can port tune the model rapidly in our circuit simulator. We can also use those extra ports to experiment with various non-adjacent couplings between resonators. What happens if we form a cascade triple by adding a simple lumped capacitor between Resonator 2 and Resonator 4?

EM Simulation Notes

- We'll start the design process with a lossless EM model.
  - PEC metal
  - No metal thickness
  - Lossless dielectric
- Lossless simulation time is about 30 seconds for seven frequencies on a quad core notebook.
- Later, when we add metal thickness, metal loss and dielectric loss, simulation time will be about 5 minutes for seven frequencies.

Before we do that, a few notes on simulation technique. We'll start the design process with a lossless EM model. We'll use perfect metal with zero thickness and a lossless dielectric. The lossless simulation time is about 30 seconds for seven frequencies on a quad core notebook. Later, when we add metal thickness, metal loss and dielectric loss, simulation time will be about 5 minutes for seven frequencies. We want to minimize the simulation time in the early stages of our design so we can make changes more rapidly.

Chebyshev Tunings: C = 0 pF

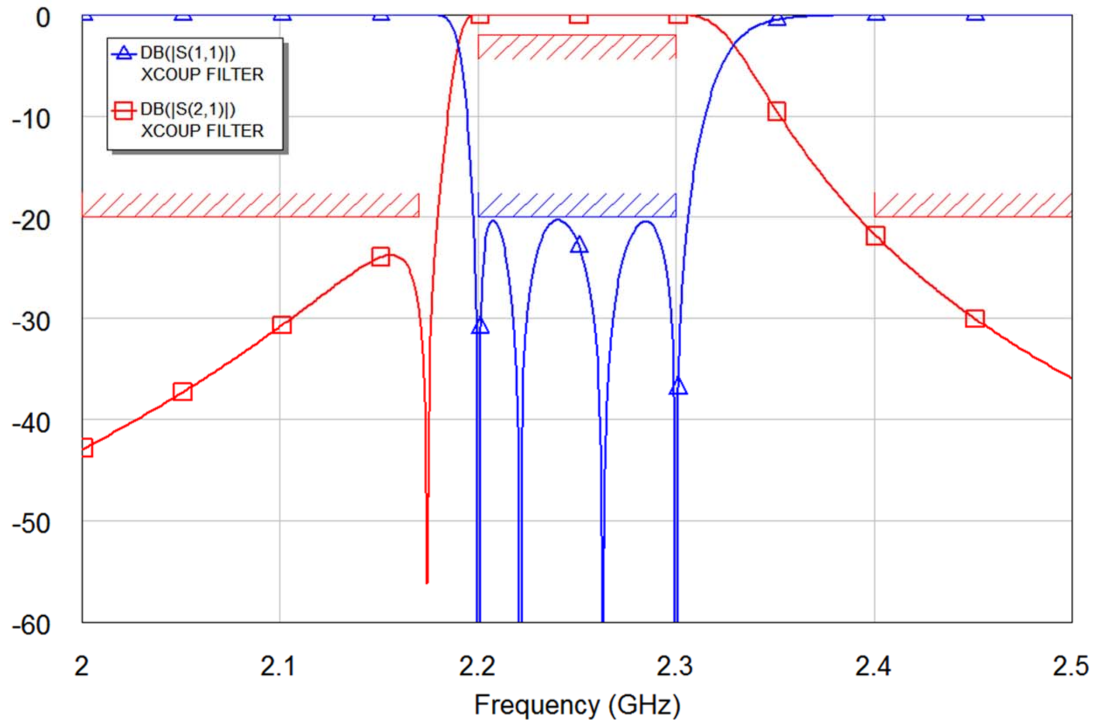


- Shunt capacitors tune resonator frequencies
- Series capacitors tune couplings
- Direct one to one correlation for physical tuning

Cross-Coupled Filter Design 10

Here is our port tuned circuit in Microwave Office. I typically redraw the symbol for the S-parameter data so that it is closer to the physical layout of my filter. The shunt capacitors tune resonator frequencies and the series capacitors tune the couplings between resonators. The beauty of the port tuning concept is the direct correlation between the tunings and the physical changes I will make to the geometry. I've saved a set of tunings for the Chebyshev case off to the right so we can compare them to the cross-coupled filter tunings. To create the cross-coupling, we start with the capacitor at 0 pF and gradually increase its value via optimization. Note we have created a cross-coupled design without resorting to any type of synthesis.

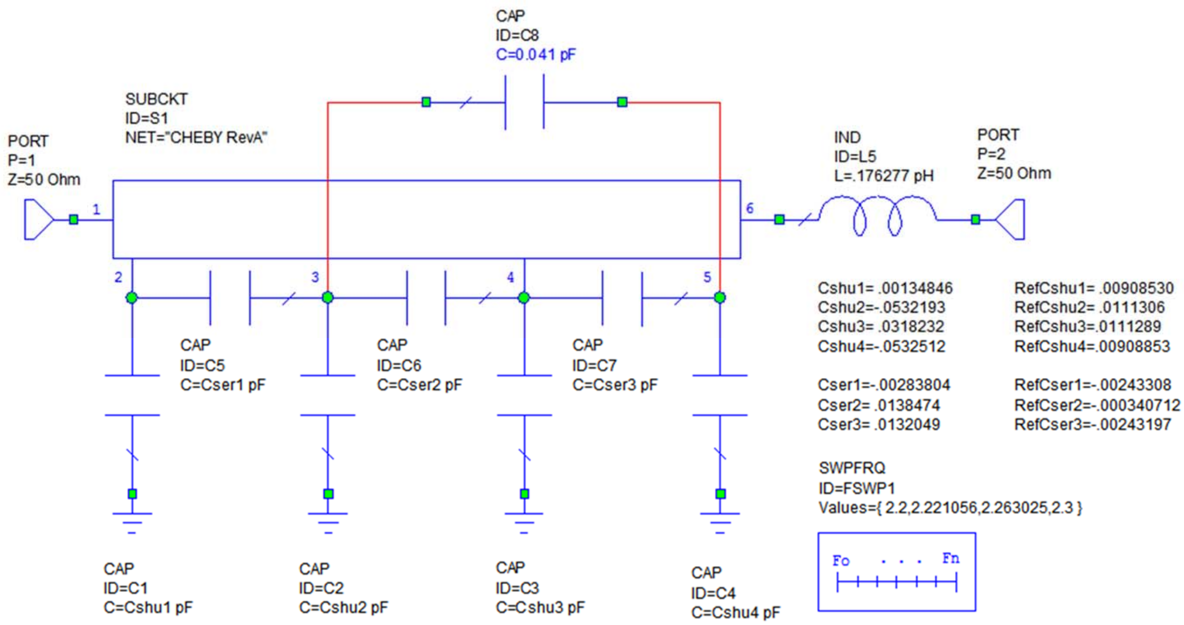
Cross-Coupled: C = 0.041 pF



Cross-Coupled Filter Design 11

Here is our first cross-coupled filter prototype. Placing the transmission zero in the lower stopband is meeting the rejection spec. And note we have lost rejection in the upper stopband. This is a byproduct of the low side zero we created. Finally note that the coupling cap is quite small. We can buy SMT caps in that range with relatively tight tolerance, but perhaps there is a better solution.

Cross-Coupled Tunings: C = 0.041 pF

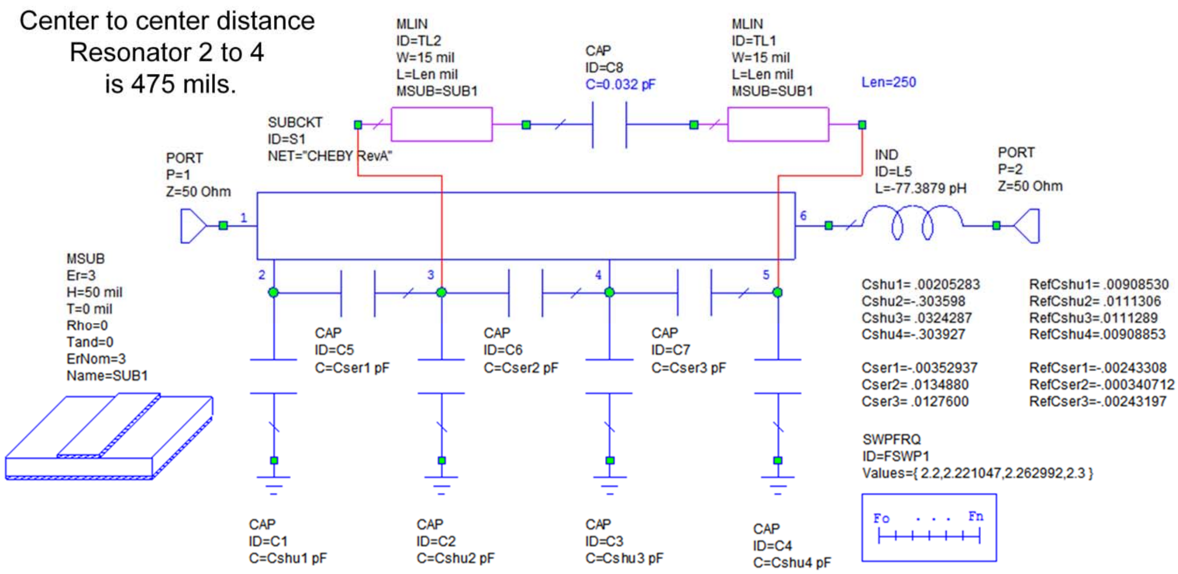


- Resonators 2 and 4 want to be shorter
- Couplings from 2 to 3 and 3 to 4 have changed

Cross-Coupled Filter Design 12

Now let's look at the tunings. The resonator tunings on Resonator 2 and Resonator 4 have gone negative, telling us those resonators want to be shorter. And the couplings between Resonators 2, 3 and 4 have also changed significantly. This is all very typical for cross-coupled filters.

Add Transmission Line: C = 0.032 pF

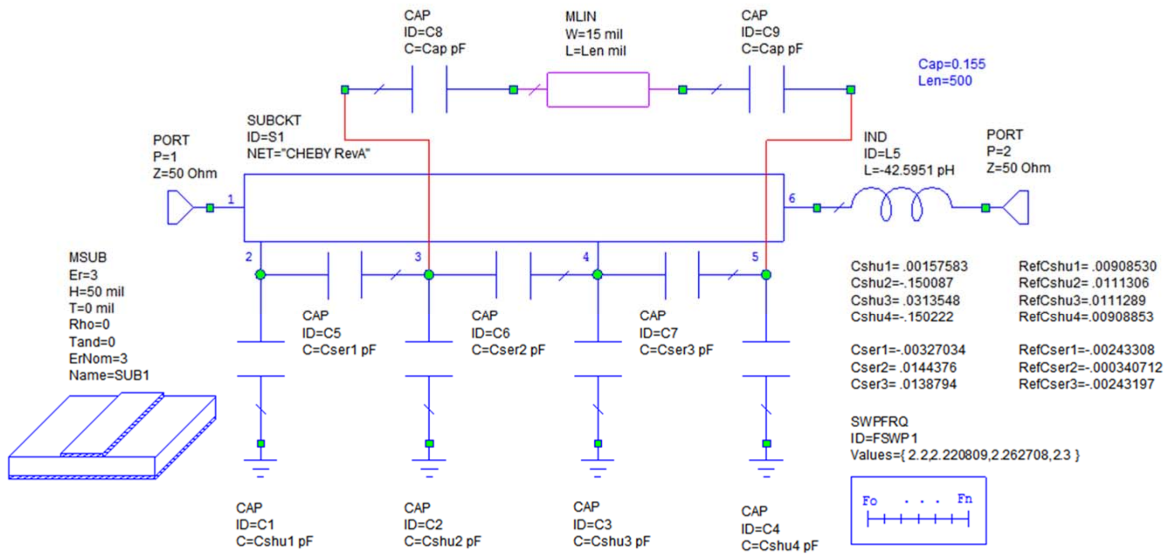


- Impact on Resonators 2 and 4 much greater
- Cross-coupling capacitor is smaller

Cross-Coupled Filter Design 13

Now let’s make our model a little more realistic. If we use an SMT cap, we need some transmission line lengths to connect to the two resonators. The center to center distance between Resonators 2 and 4 is 475 mils. We’ll round that up to 500 mils just to be safe. And we’ll choose a line width of 15 mils. After optimizing this new network, the results are quite different. The negative tunes on Resonators 2 and 4 are now much larger and the coupling cap is smaller.

Two Caps in Series: C = 0.155 pF

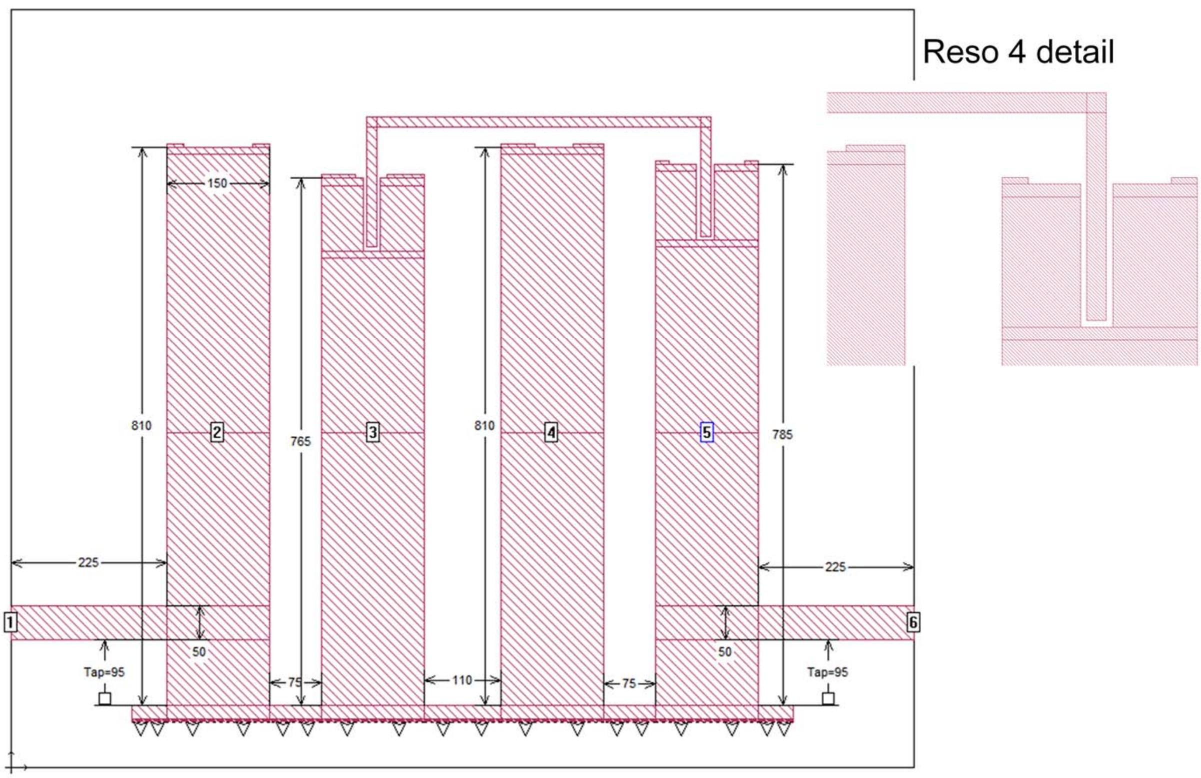


- Impact on Resonators 2 and 4 is less than single cap
- Cross-coupling capacitor is larger

Cross-Coupled Filter Design 14

One way to make the coupling cap larger is to use two capacitors in series. Now we will put all the transmission line length between the two caps. The negative tunes on Resonators 2 and 4 are now half of what they were with the single cap. Placing SMT caps at the open ends of two resonators can certainly be done, but it may be a bit of a modeling challenge. We are working in a very sensitive region with a lot of fringing fields off the ends of the resonators. Perhaps we can use a printed geometry to realize this coupling network.

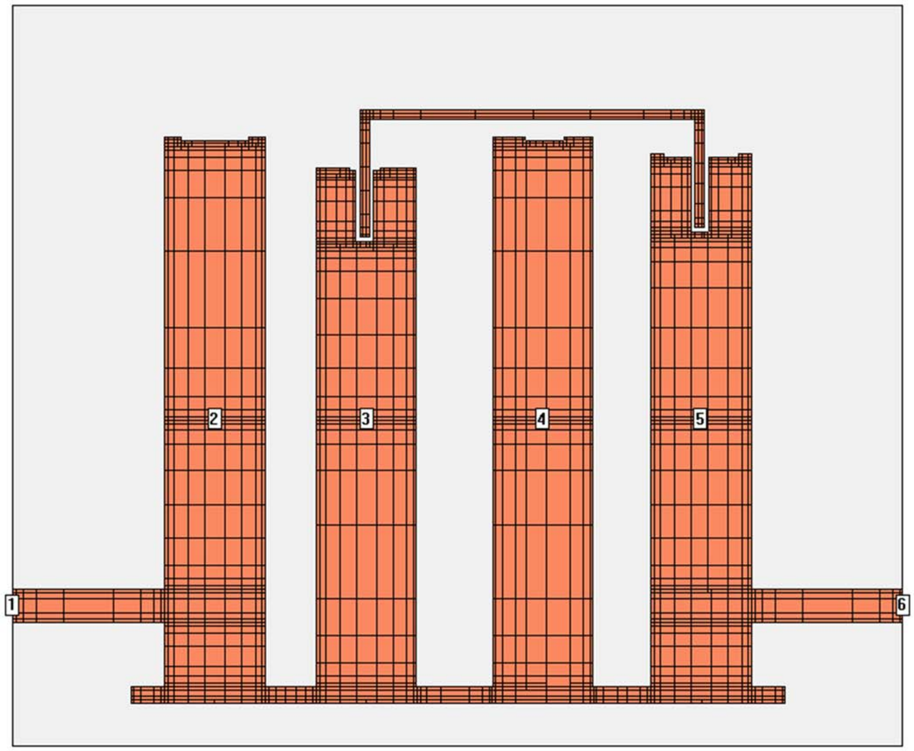
Two Caps in Series: Printed Caps



Cross-Coupled Filter Design 15

This is the geometry we are proposing. We have created simple gap caps or interdigital caps in the resonator open ends. You can see the detail for Resonator 4 to the right.

Mesh Control

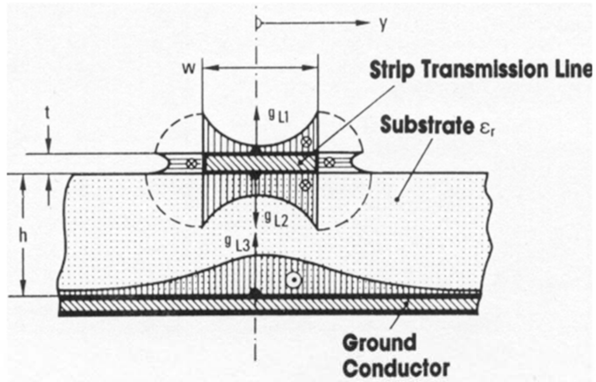


Cross-Coupled Filter Design 16

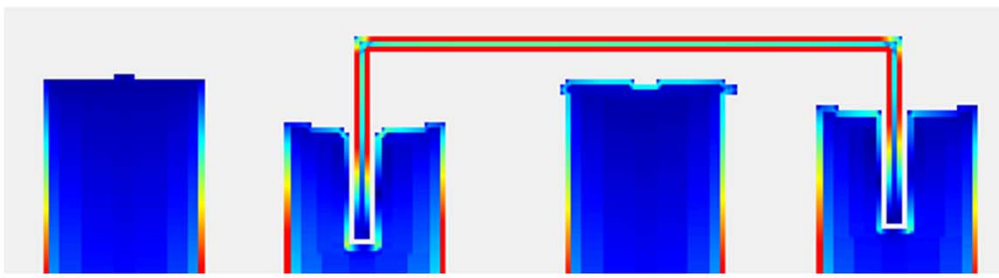
You may have noticed extra polygons in the open end regions. These have been placed to help guide the meshing process. Without these extra polygons, the finer mesh we have created at the open ends and around the capacitors tends to propagate down the length of the resonators. This can have a large impact on simulation time. There are other tools in Sonnet **em** that we can use to control meshing on a polygon by polygon basis.

Why Use a 15 mil Wide Line?

- 15 mil line and 5 mil gap chosen to reduce etch tolerance.
- It is also a meshing issue.
- On a 5 mil grid, a 15 mil wide line has three cells across the width.
- Three is the smallest number of cells we can use to approximate the non-uniform current distribution across the width.
- We can test for convergence by reducing the grid size.



Hoffman, *Handbook of Microwave Integrated Circuits*. Norwood: Artech House, 1987.



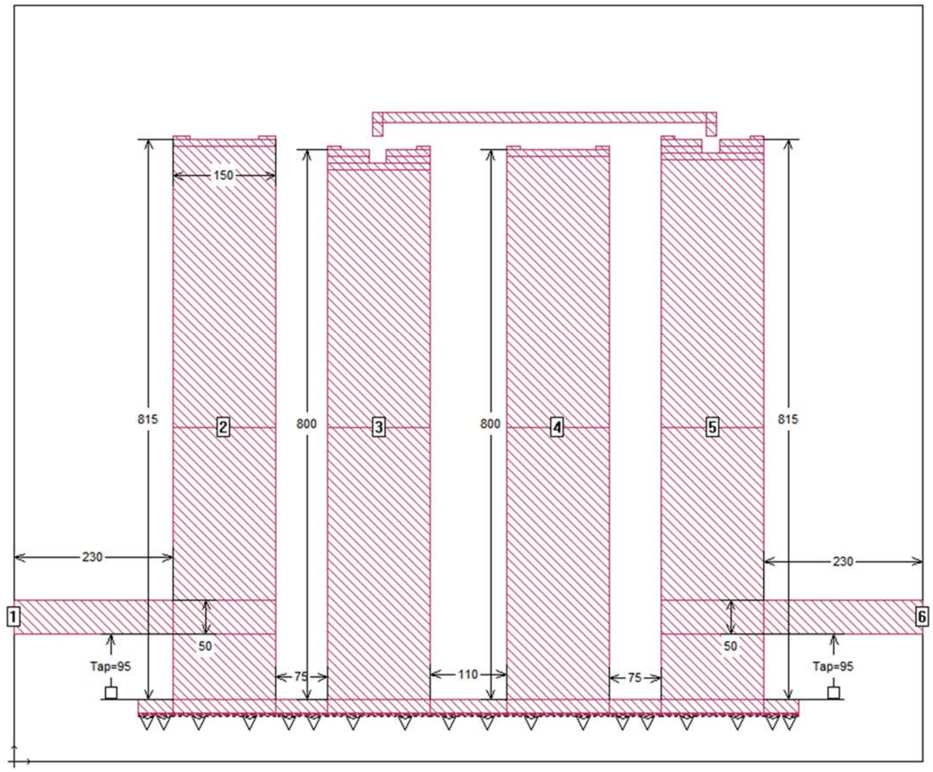
Cross-Coupled Filter Design 17

Why did we choose a 15 mil wide line for our coupling network? Hopefully, a 15 mil line and a 5 mil gap will be easy for the PCB manufacturer to control. We don’t want to push the limits of what is possible.

It is also a meshing issue in Sonnet **em**. On a 5 mil grid, a 15 mil wide line has three cells across the width of the strip. Three is the smallest number of cells we can use to approximate the non-uniform current distribution across the width. In the figure to the right, we see a cross section of a rectangular microstrip with finite thickness. The relative current magnitudes are plotted for all four surfaces. We see that the currents tend to bunch up at the corners.

In the current plot from Sonnet **em** we can clearly see high currents on the edges of the 15 mil trace and lower current in the center. Is this model good enough? The only way to know for sure is to use a smaller grid and solve the problem again.

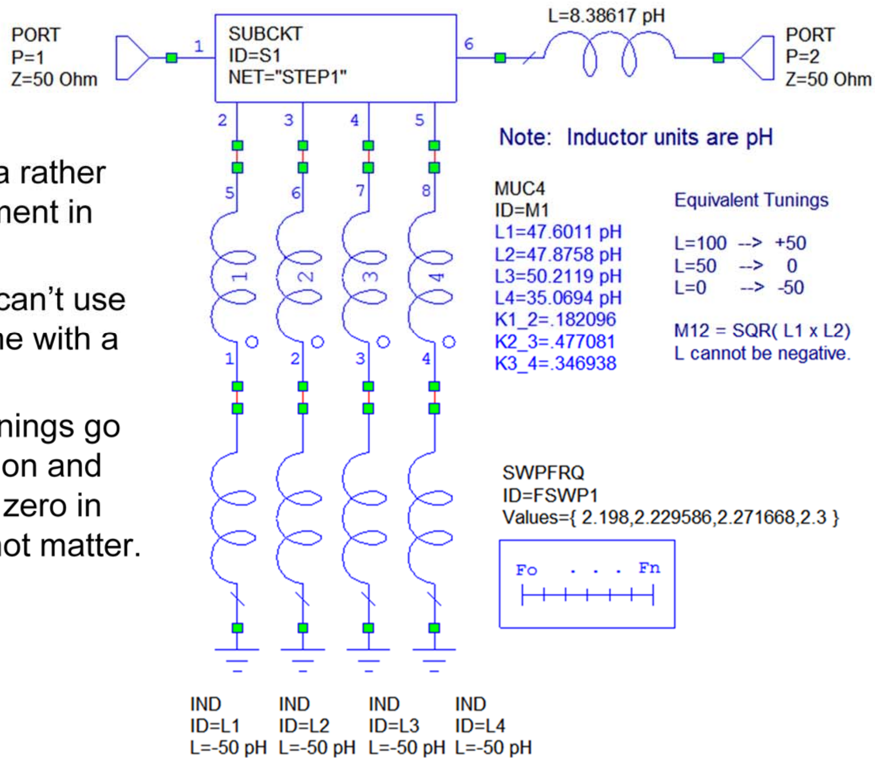
Step 1 Layout



Cross-Coupled Filter Design 18

Now we are ready to proceed with our design. In Step 1, we put the cross-coupling structure in place with little or no coupling to the resonators. Notice we have moved the tuning ports to the center of the resonators. These are series gap ports that introduce very little error into the EM simulation.

Step 1 Tunings



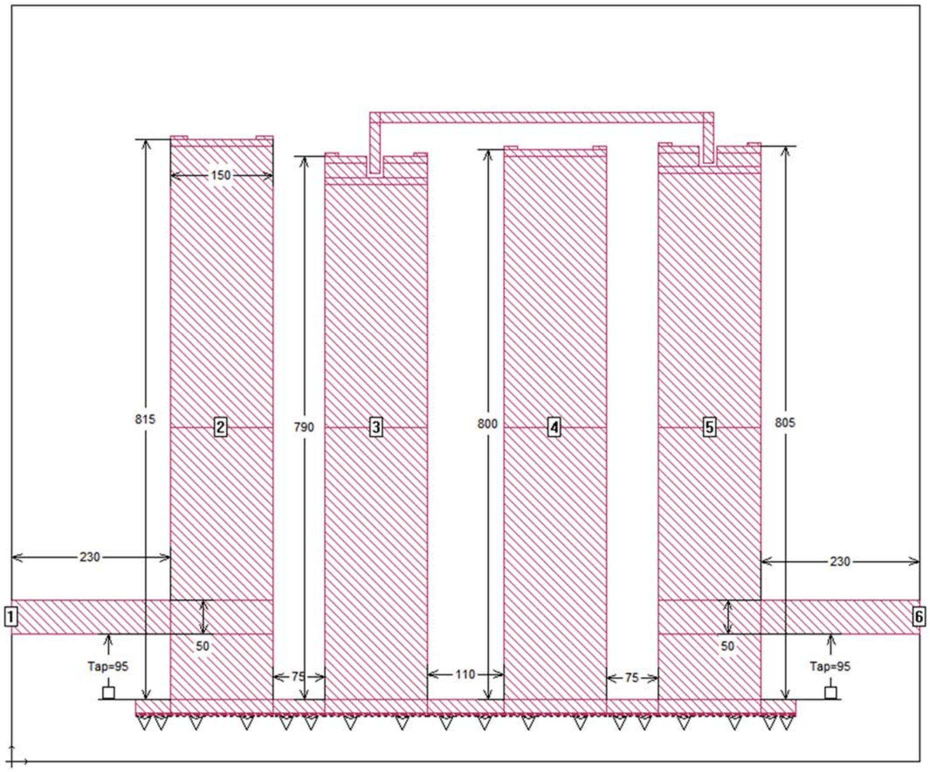
- Isn't an inductor a rather crude tuning element in this case?
- Yes it is. But we can't use a transmission line with a series gap port.
- As long as the tunings go in the right direction and the tunings go to zero in the end, it does not matter.

Cross-Coupled Filter Design 19

Port tuning with the series gap ports requires a couple of tricks. The coupled inductor array is our basic tuning element. Positive and negative inductors with shift the frequency of the resonators. The coupling between resonators can be modified using the mutual inductances in the array. But the definition of mutual inductance requires the inductors in the array to always be positive. So how do we tune in the negative direction? We add -50 pH inductors in series with the inductor array to offset the tuning. Now 100 pH in the array corresponds to +50 pH net tuning, 50 pH in the array corresponds to 0 pH net tuning and 0 pH in the array corresponds to -50 pH net tuning.

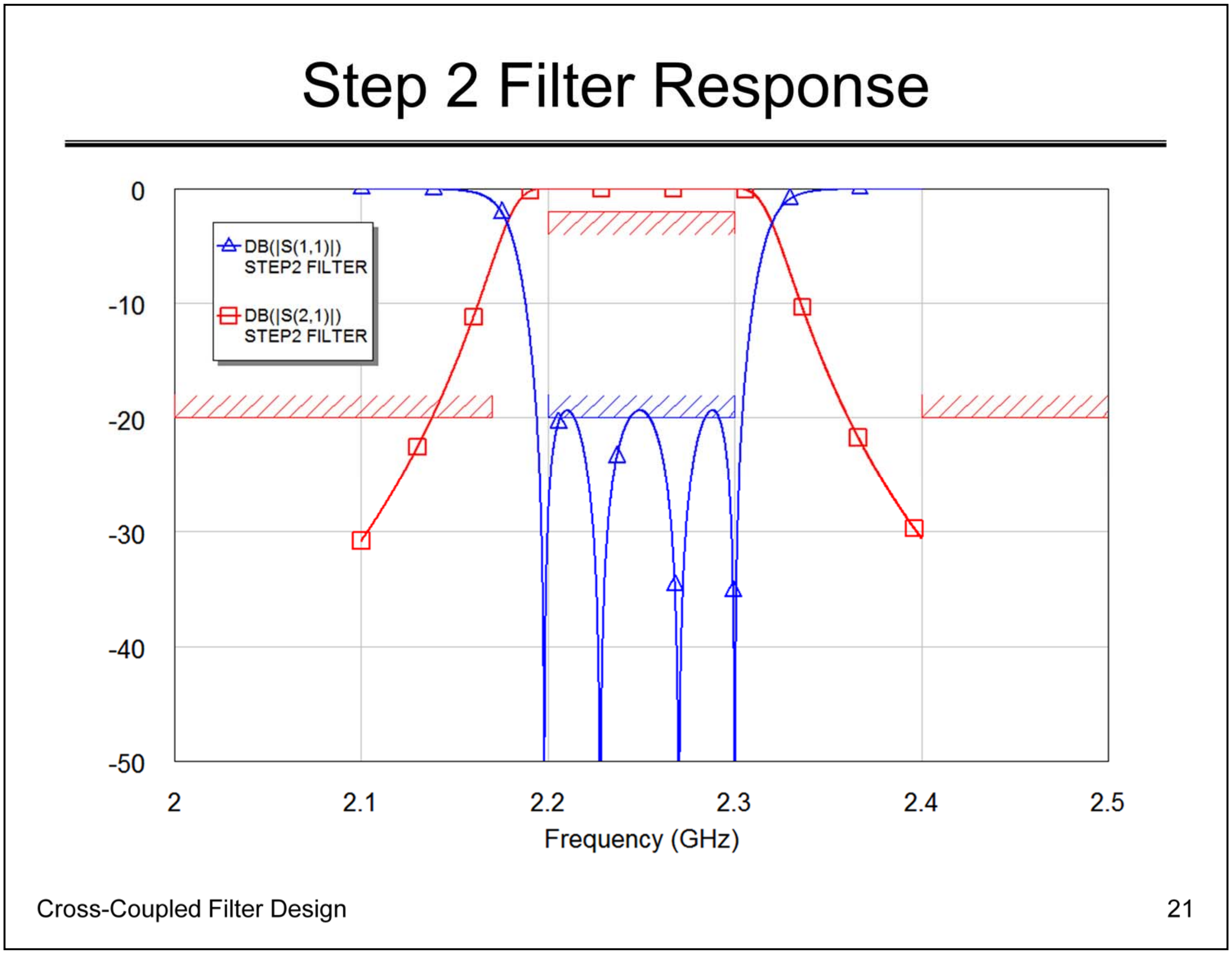
We can also ask, isn't an inductor a rather crude tuning element in this case? Wouldn't we rather have a transmission line of the same impedance as our resonator? Yes, the inductor is crude, but we can't use a transmission line with a series gap port. But, as long as the tunings go in the right direction and the tunings go to zero in the end, the type of tuning element that we use does not matter.

Step 2 Layout



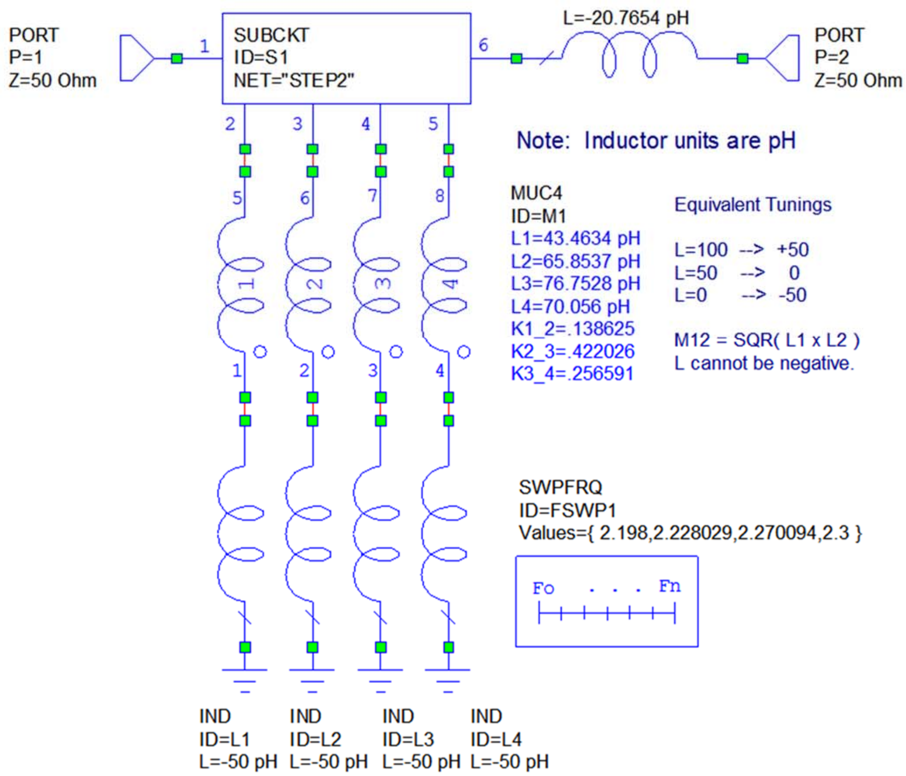
Cross-Coupled Filter Design 20

In Step 2 we’ve made the cross-coupling a little stronger and Resonators 2 and 4 are getting shorter.



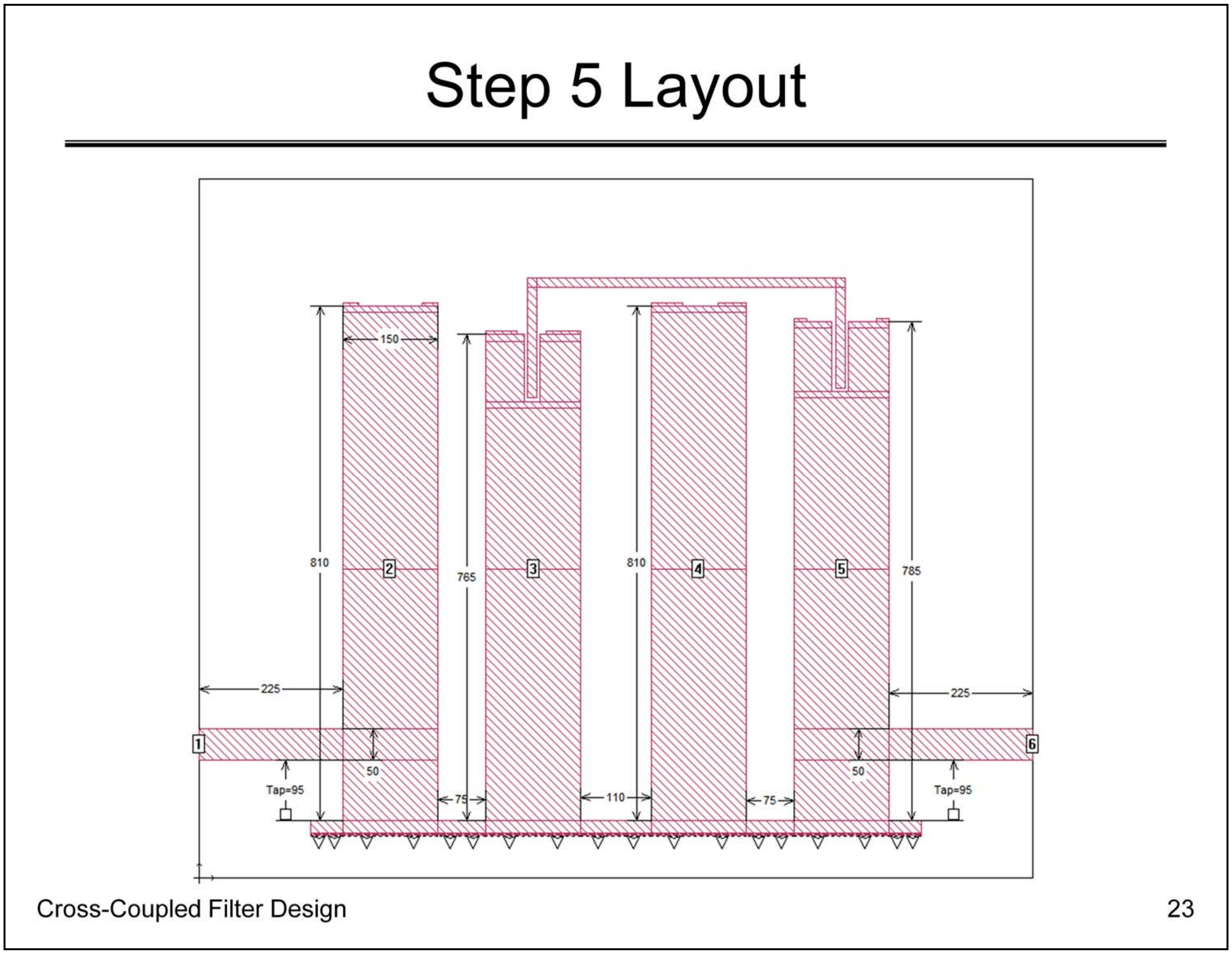
With this small cross-coupling the filter response is very symmetrical. This might be useful for another application with a more symmetrical rejection specification. For now we keep increasing the cross-coupling and shortening the resonators in small steps using EQR_OPT_MWO.

Step 2 Tunings



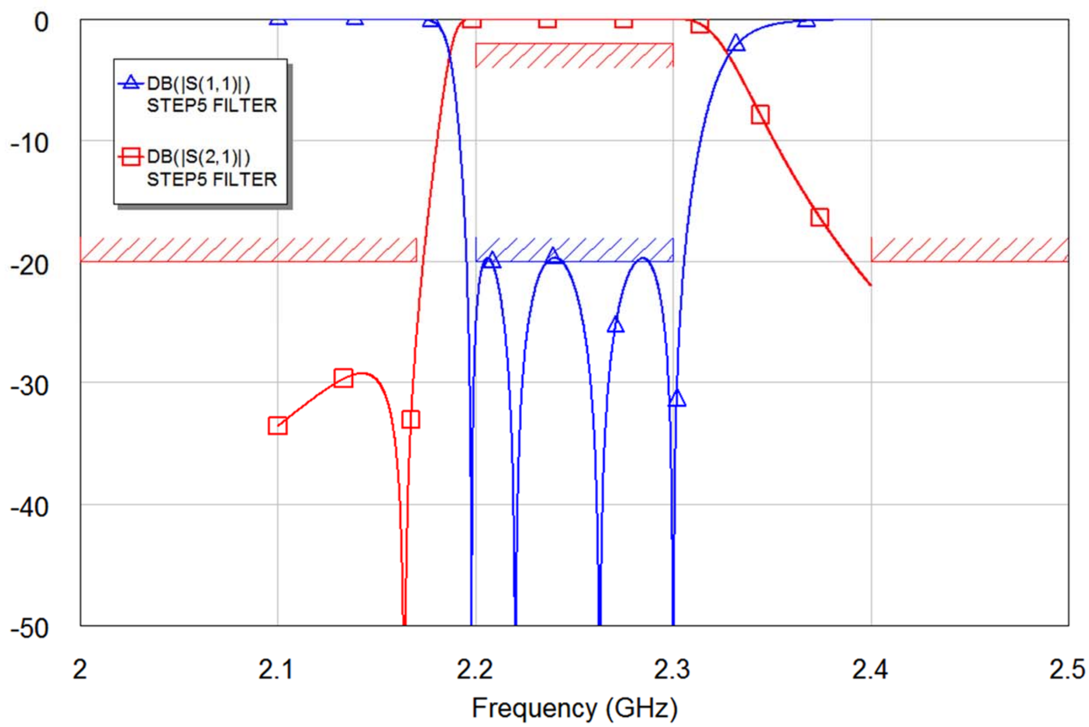
Cross-Coupled Filter Design 22

These are the tunings for Step 2. We want to keep the resonator tunings near 50 pH but the don’t have to be exact at this point. And we are ignoring the coupling tunes for now.



We’ve jumped ahead to Step 5 to save time. The cross-coupling is now strong enough to place the transmission zero very close to where we want it. Now we’ll shift our focus to the coupling errors.

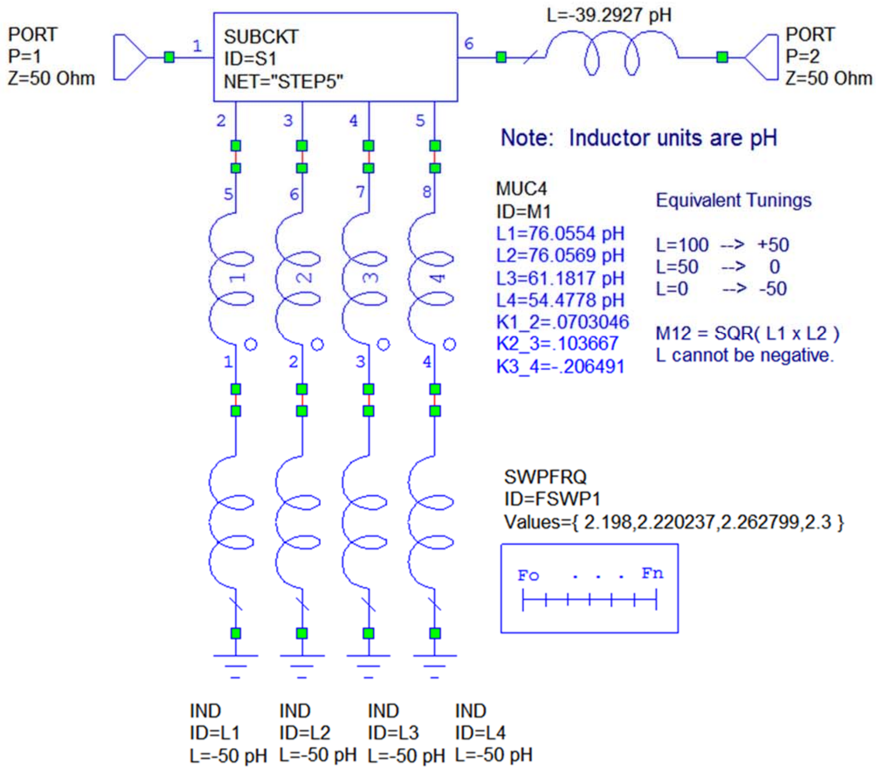
Step 5 Filter Response



Cross-Coupled Filter Design 24

Here is the filter response at Step 5. It is very similar to our earlier simplified two cap model.

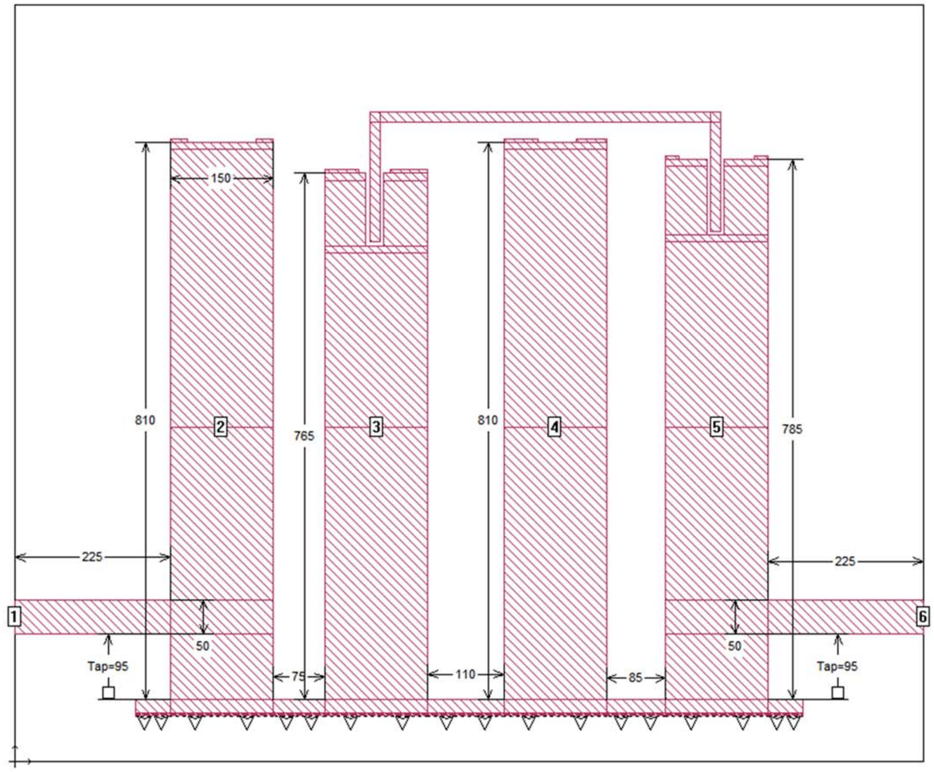
Step 5 Tunings



Cross-Coupled Filter Design 25

The largest coupling correction is K3_4 and it is negative, so we want to make the third gap larger.

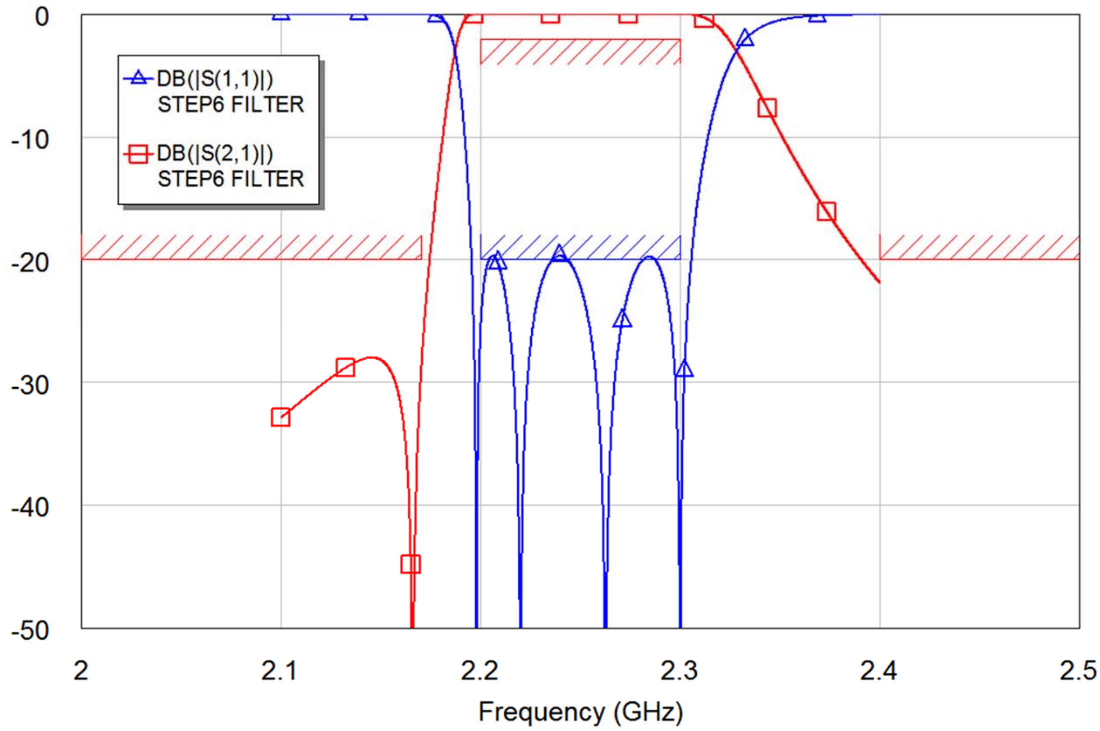
Step 6 Layout



Cross-Coupled Filter Design 26

In Step 6 we have made the third gap 10 mils bigger.

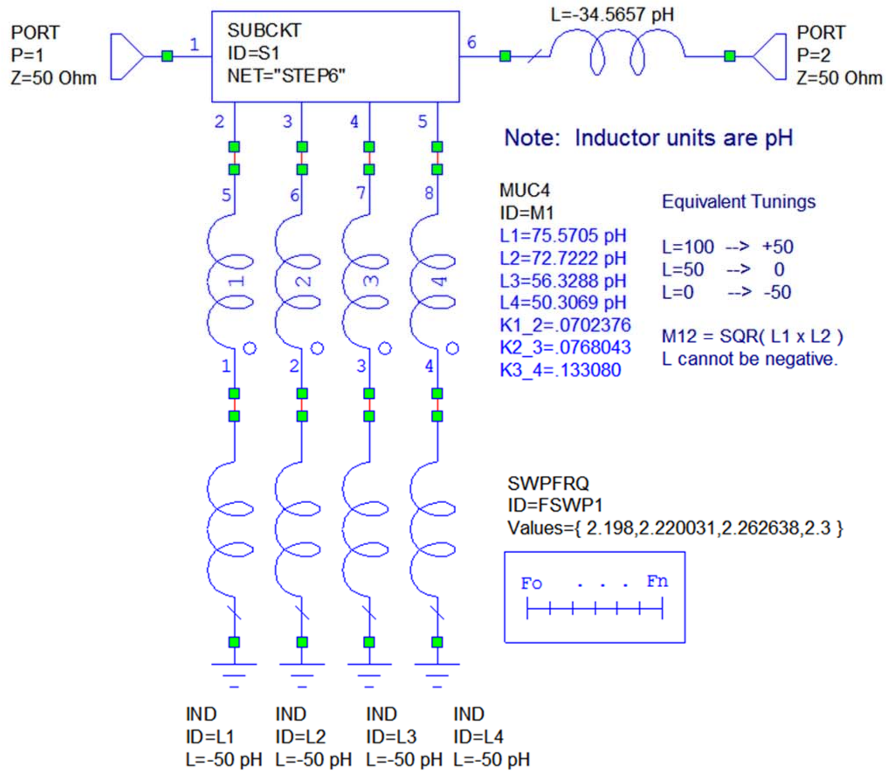
Step 6 Filter Response



Cross-Coupled Filter Design 27

This is the Step 6 filter response.

Step 6 Tunings



Cross-Coupled Filter Design 28

We overshot the correction to K3_4 and now all the resonator couplings want to be slightly stronger.

Next Steps

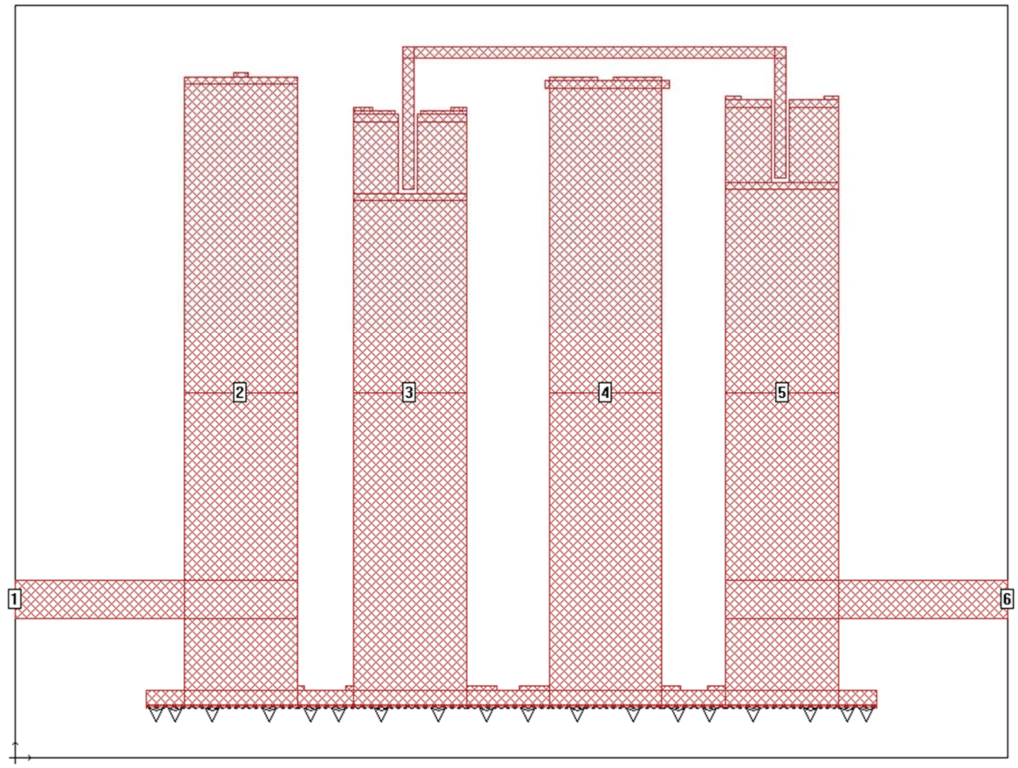
- We've gone about as far as we can in lossless mode.
- Time to add loss and metal thickness.
  - Both have a large impact on simulation time.
  - I used to add them one at a time.
  - But they tend to compensate one another, so it is better to add both at once.
- Metal thickness affects the inductance per unit length.
  - It modifies the resonator length.
  - It modifies the resonator impedance.
  - It has little to no impact on capacitive coupling in this case: the gaps are very large.

Cross-Coupled Filter Design 29

We're now getting close to our final solution and it's time to add losses and metal thickness. Both of these have a large impact on simulation time. I used to add them one at a time, focusing strictly on simulation time. But I noticed that adding one drove me away from my starting solution and adding the second one drove me back towards the starting solution. So loss and metal thickness tend to compensate one another and it is better to add both at once.

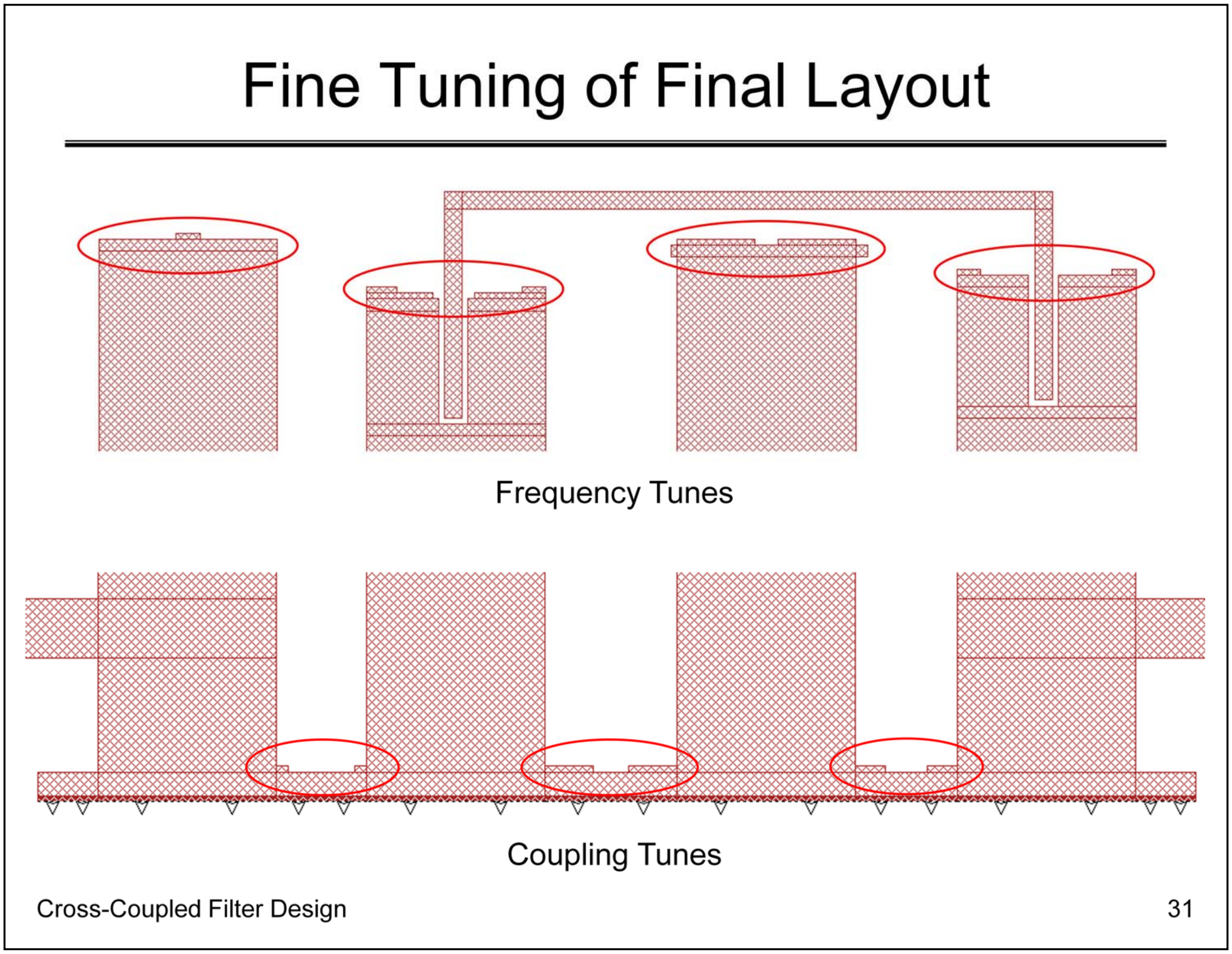
Our metal thickness is 0.7 mil and the resonator width is 150 mils, which leads us to question the importance of metal thickness in the simulation. Metal thickness affects loss and the inductance per unit length of the resonators. Thus thickness modifies the resonator lengths and the resonator impedances. Thickness has little or no impact on capacitive coupling in this case: the gaps are very large.

Final Layout



Cross-Coupled Filter Design 30

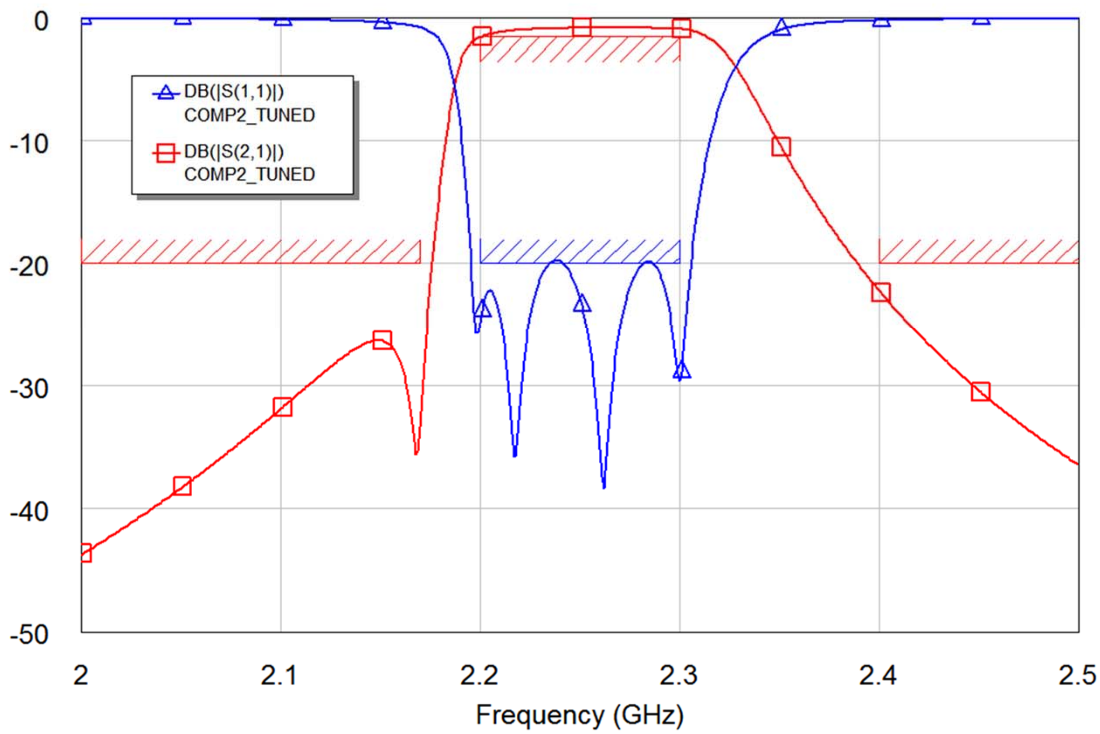
After fine tuning with loss and metal thickness here is our final filter layout. Resonators 2 and 4 are clearly shorter and the gaps between resonators are now asymmetrical.



In the final stages of tuning we can add and subtract metal one cell at a time at the resonator open ends to fine tune frequencies. There is no requirement for symmetry when we place the tunes. Note the slight asymmetry in the Resonator 3 tunes. We can slide a single tune across the width of the resonator and get additional fine control. Adding and subtracting metal between the resonators at their shorted ends fine tunes the couplings. For larger coupling corrections we can add or subtract metal on the long edges of the resonators.

We call this process “patch tuning.” It completely overcomes the fixed grid limitations of the closed box MoM simulators. Instead of struggling to move a line length or width in small increments, we leave the major geometry fixed and add or subtract several cells of metal. This is exactly how we would tune a microstrip circuit in the lab, if we had microscopic control of how we added and subtracted metal. This is a far cry from the old days of silver paint, gold ribbons and diamond scribes.

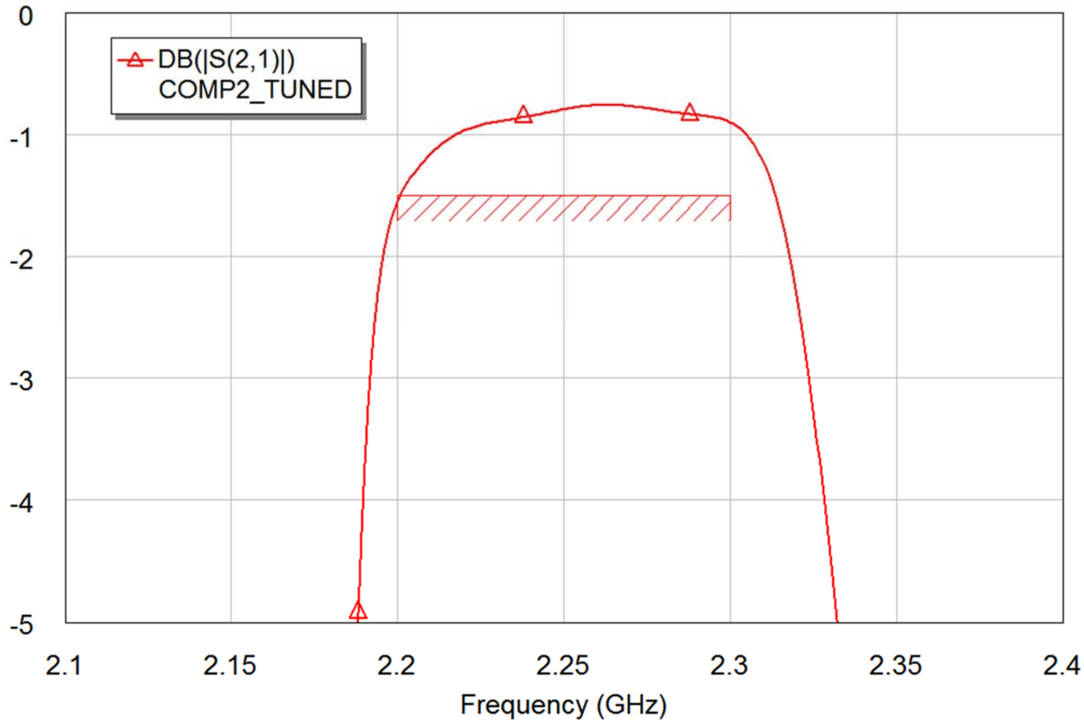
Final Tuned Filter Response



Cross-Coupled Filter Design 32

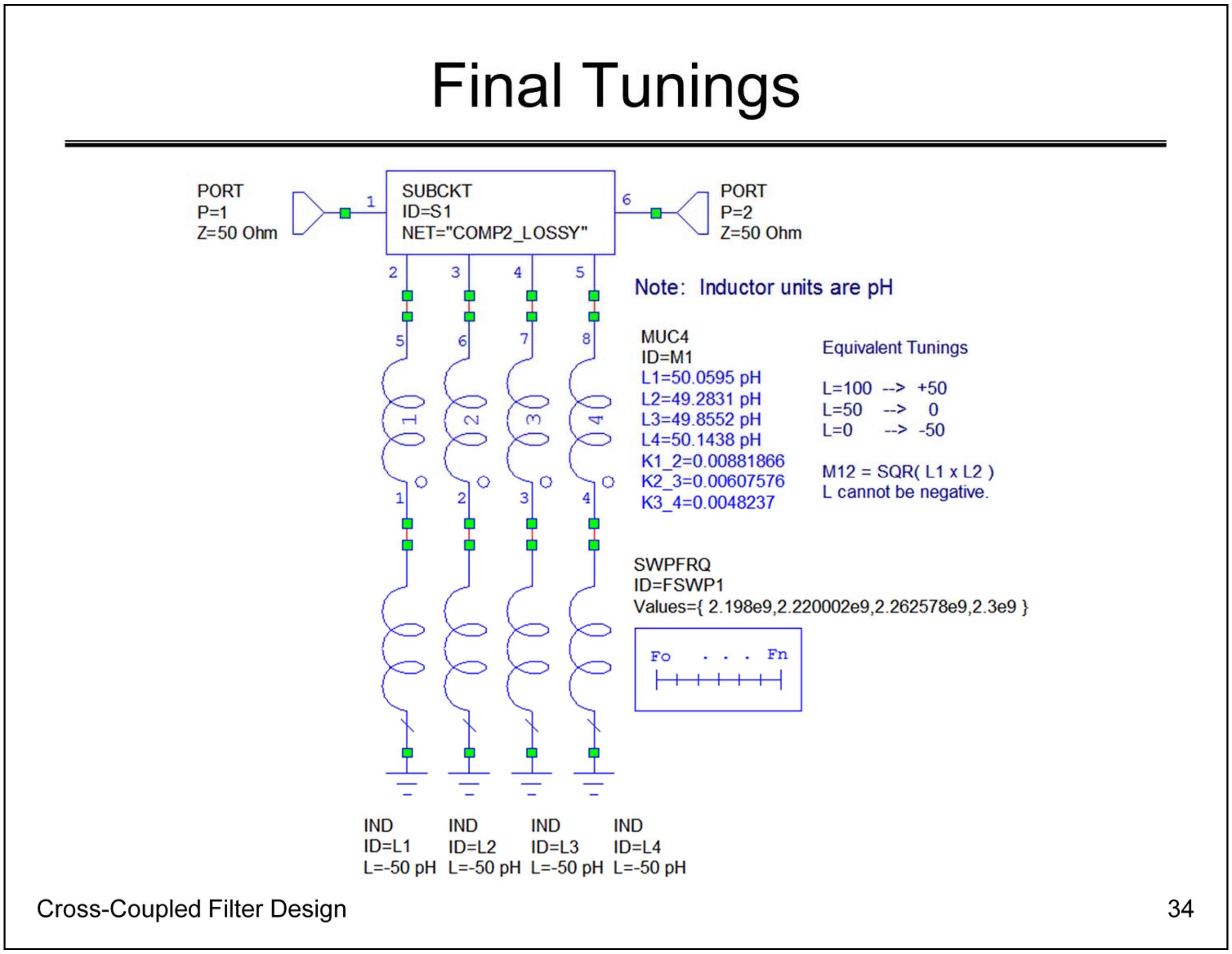
Here is the final frequency response of our filter. Our optimization method is not as exact in the lossy case, but this is certainly a usable result.

Final Tuned Filter Response



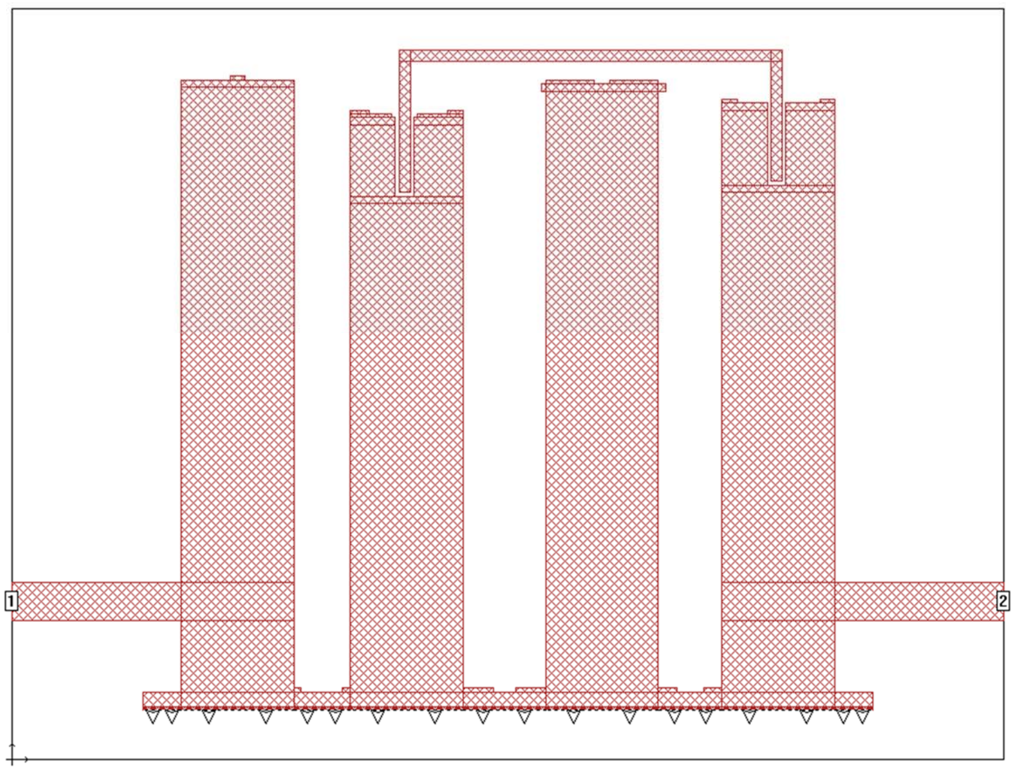
Cross-Coupled Filter Design 33

A closer look at insertion loss.



Here are the final tunings with loss and thickness. Note all the tunes are very small. Remember that 50 pH in the inductor array gives us zero net tuning.

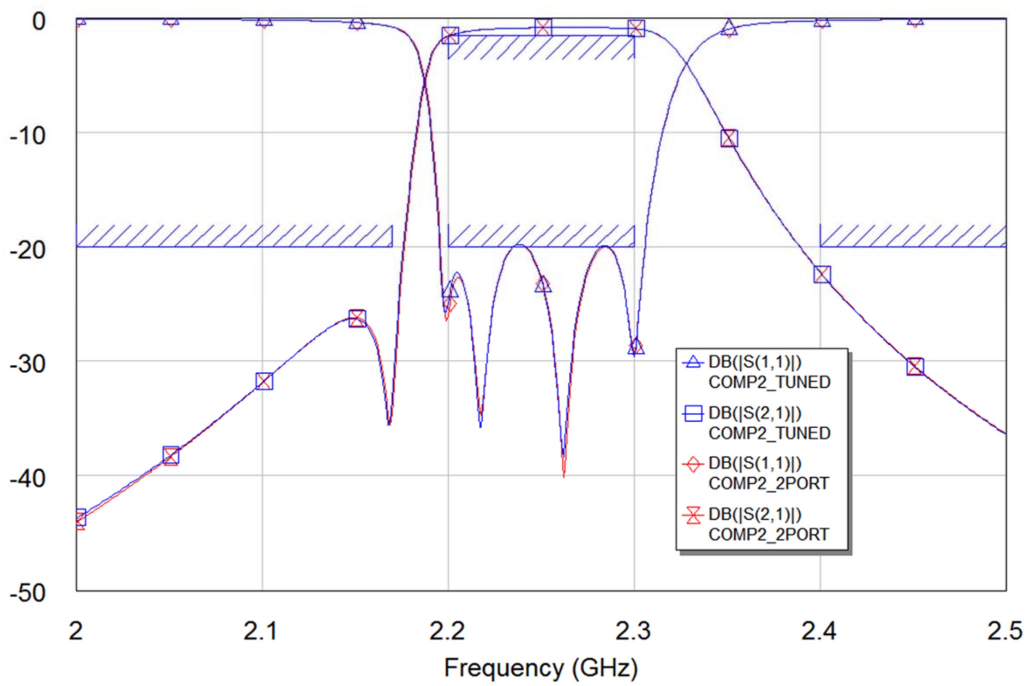
Final Two Port Simulation



Cross-Coupled Filter Design 35

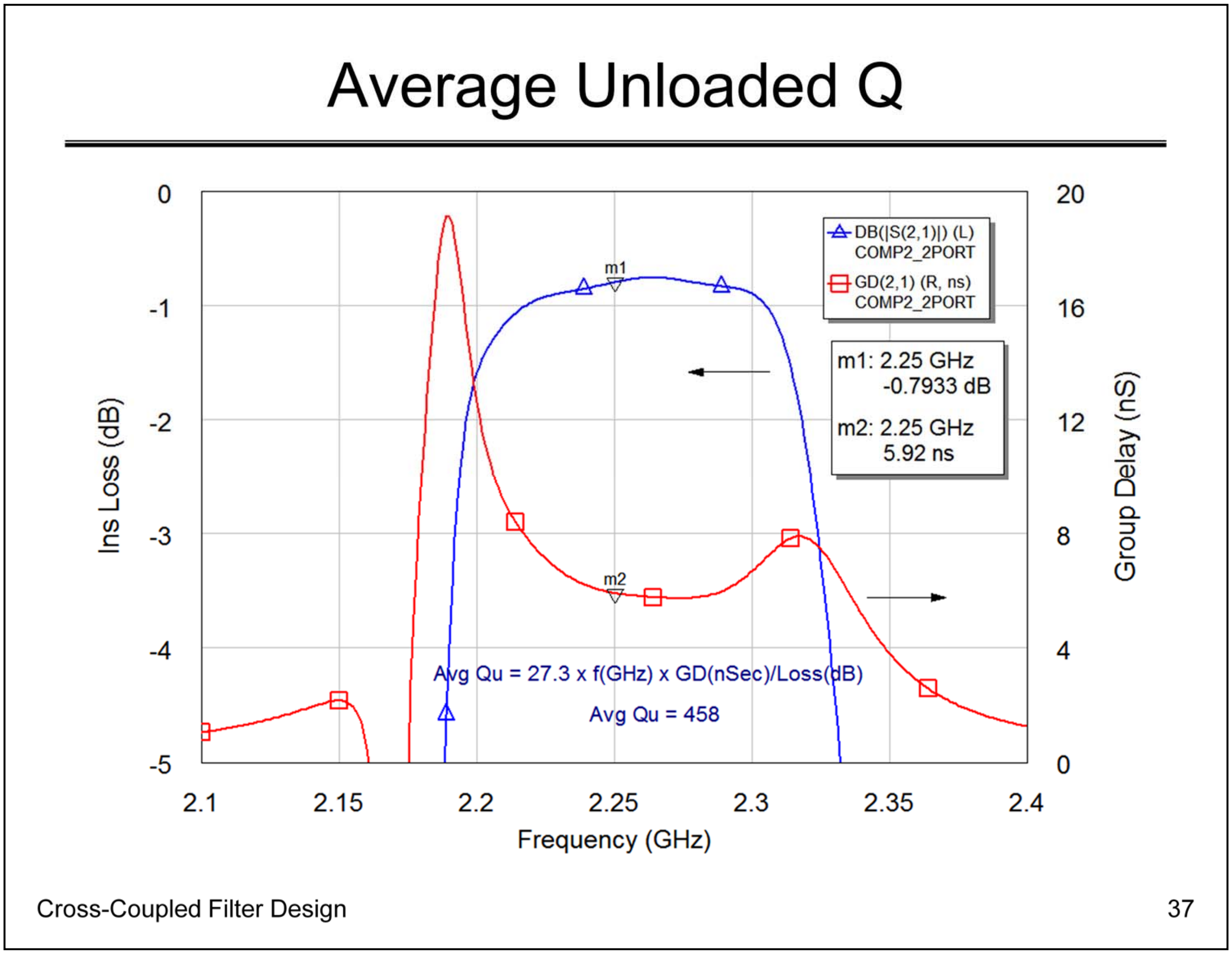
We can check our tuned results by removing the tuning ports and simulating just the two port network.

Compare Tuned and Two Port Sims

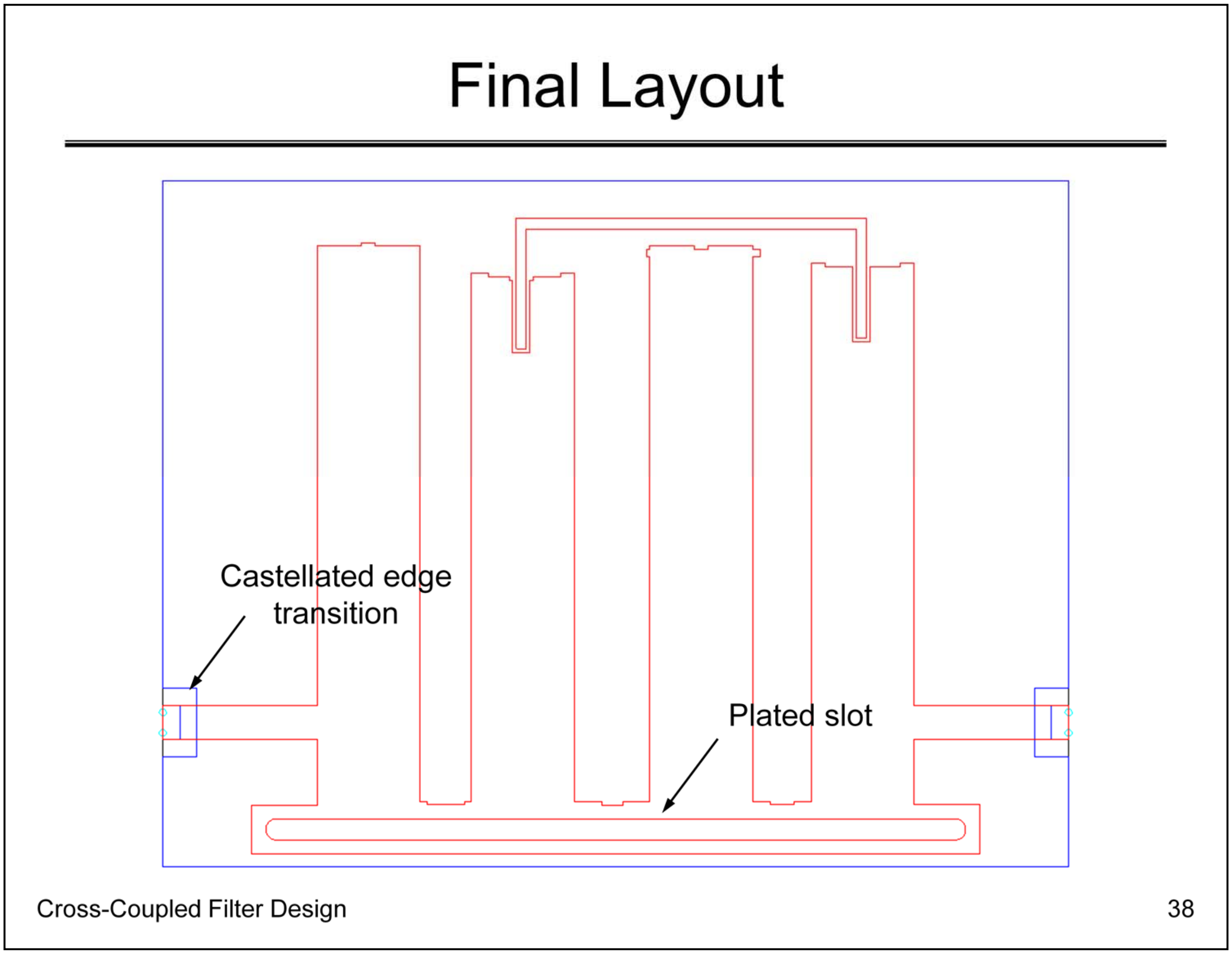


Cross-Coupled Filter Design 36

This plot has four traces, the final port tuned results (red) and the two port simulation (blue). This is confirmation that our tuning ports introduce very little error into the design process.



From either final simulation we can estimate the average unloaded Q for our filter. We simply need the insertion loss and group delay at midband. The simple formula on the slide gives us the average unloaded Q. This is a useful calculation to do from your measured data as well.



Here is a CAD drawing of our final layout. Top layer metal is red and bottom layer metal is blue. We have designed a simple castellated edge transition at the input and output. We also need a metal cover for our filter that matches the size of the simulation box in Sonnet **em**.

Conclusion

- We can design cross-coupled microstrip filters without resorting to any kind of synthesis.
- Starting from a Chebyshev prototype design we simply “grow” the desired cross-coupling using optimization.
- The port tuning process gives us unambiguous tuning instructions for each resonator and gap.
- The patch tuning technique allows us to fine tune our design using a relatively coarse simulation grid.
- We can apply these same techniques to other topologies, such as the microstrip edge-coupled.

We have designed a simple cross-coupled microstrip filter without resorting to cascade synthesis or coupling matrix synthesis. Starting from a Chebyshev prototype design we first experimented with different topologies for the cross-coupling network. Then we “grew” the desired cross-coupling network into our filter layout using optimization. Because our filter optimizer is so robust, this is actually a quite efficient and intuitive process. The port tuning process gives us very clear tuning instructions for each resonator and gap in the filter, without any complex mathematics. The patch tuning technique allows us to fine tune our design using a relatively coarse simulation grid. Finally, we can apply these same techniques to other topologies, such as the microstrip edge-coupled.