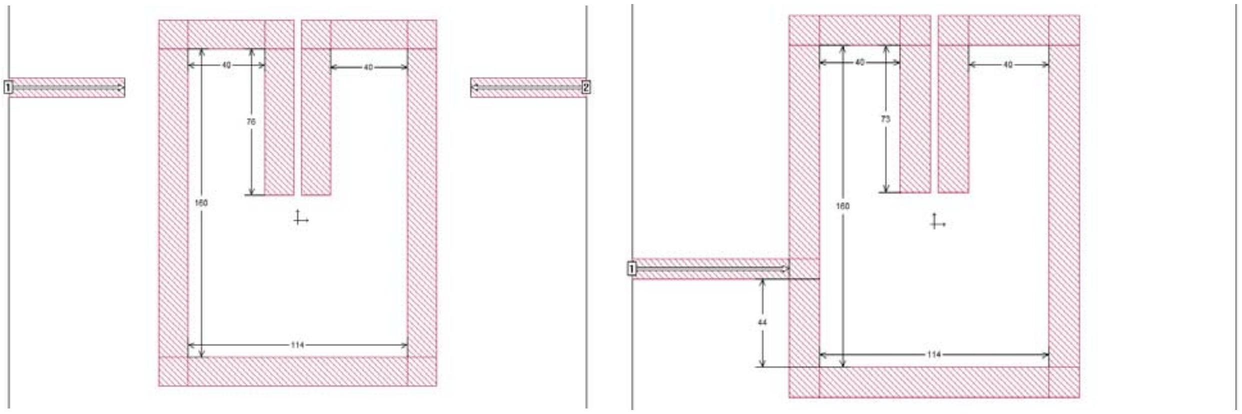
Port Tuning a Microstrip Folded Hairpin Filter

Daniel Swanson
DGS Associates, Boulder, CO
www.dgsboulder.com

In this tutorial we will replicate a design example that has been used by others. The design goal is an N=5 bandpass filter with 10% bandwidth centered at 3 GHz. Ten mil thick alumina was chosen for the substrate. At this frequency we would typically choose 20 or 25 mil thick alumina and widen the resonator strips to reduce the insertion loss. A thicker substrate will increase the coupling between resonators while wider strips will decrease the coupling. Using Dishal's K&Q method [1,2] we can rapidly get to an EM based prototype of the filter. Figure 1 shows the EM simulations used to center the resonator frequency and find the correct tap point.



(a) Resonator frequency

(b) Resonator tap point

Figure 1. Sonnet **em** simulations used to find center frequency and tap point.

Normally we would also simulate the coupling between resonators, but in this case there are only two unique gaps and we can make a guess based on experience. Our first guess was 4-6-6-4 mils for the gaps. Next we tried 5-7-7-5 mils. Figure 2 shows the initial layout of our filter. Figure 3 shows the two port simulation results.

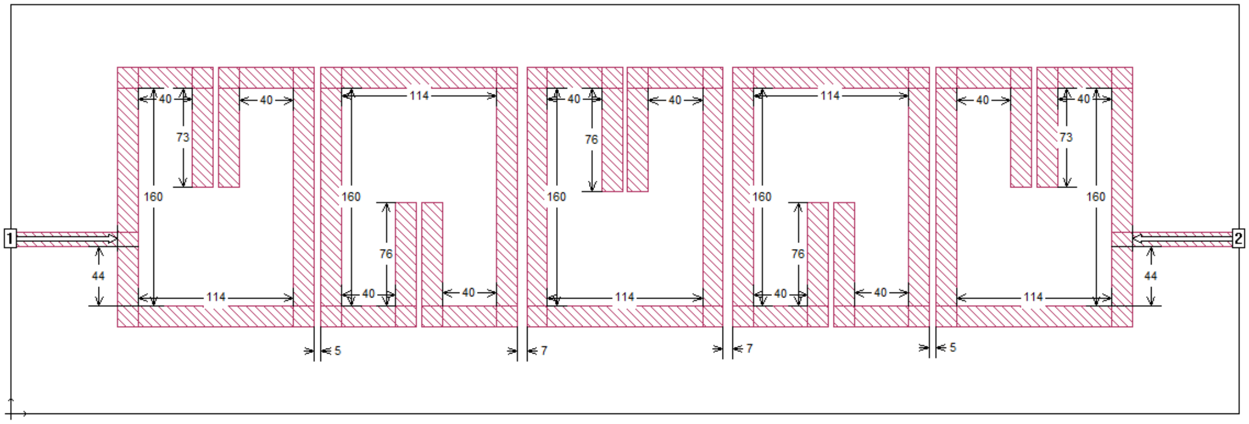


Figure 2. Sonnet **em** analysis of initial layout.

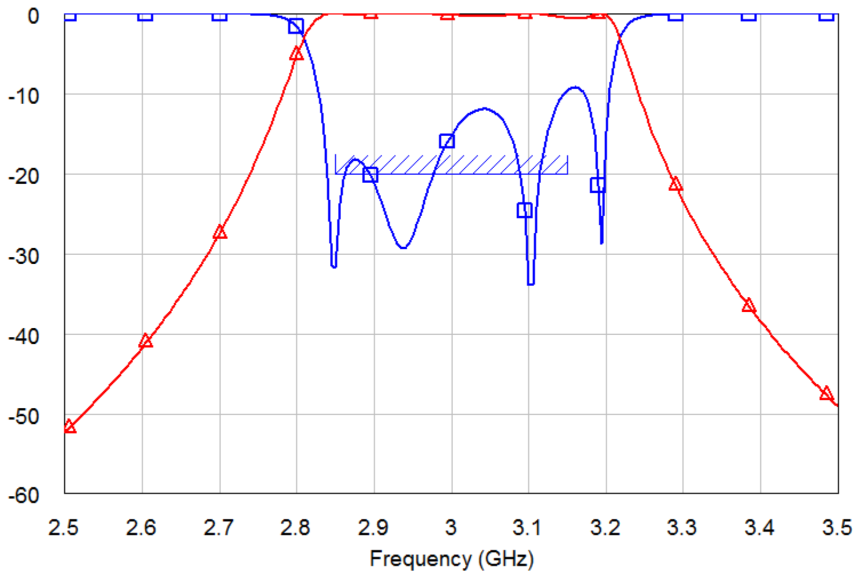


Figure 3. Simulation of initial EM based prototype.

As can be seen in Figure 3, the filter is slightly over coupled, but otherwise it is a good starting point for port tuning and optimization. Next we need to place ports for tuning. In this case we will place series gap ports at the base of each resonator, Figure 4. The series gap ports introduce very little error into the EM simulation. We also increased the interior filter gaps to 8 mils and added 1 by 30 mil strips of metal in the gaps to start the fine tuning process.

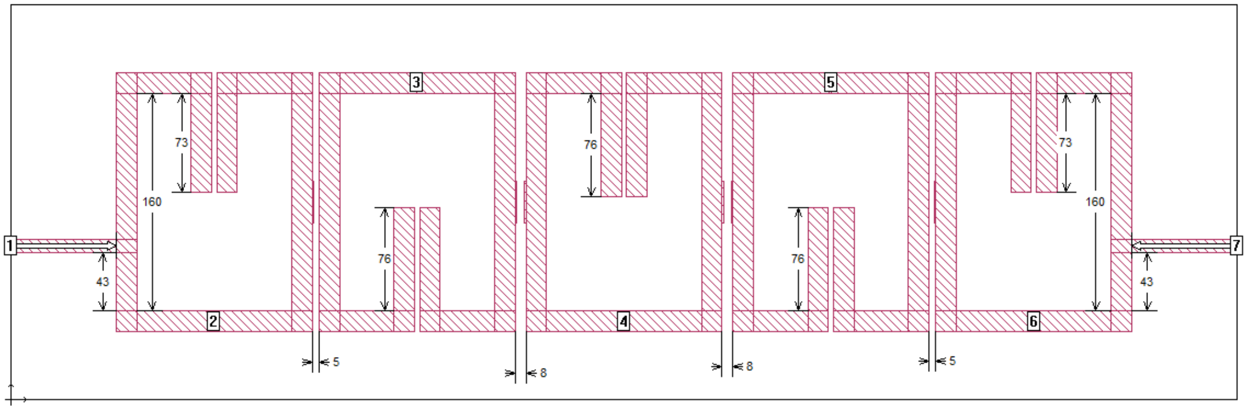


Figure 4. Series gap ports added for port tuning.

We only need seven total ports to optimize the layout. It is possible to use Co-Calibrated ports in Sonnet **em** and insert analytical microstrip models into the EM layout via the circuit simulator. The resulting schematic can become quite complex. However, using microstrip models that match the physical layout is actually not necessary. Our Microwave Office port tuning schematic is shown in Figure 5. The inductors to ground at Port 2 through Port 6 will tune the resonator frequencies. As long as the inductors tune the resonator in a predictable way and the tunes go to zero at the end of the process, it does not matter what type of element we use. Using the coupled inductor model we can fine tune the adjacent couplings between resonators: the nonadjacent couplings are set to zero. Again, the ports are not physically collocated, but as long as our tuning drives the coupling in a predictable way, and the tunes go to zero at the end, it does not matter how we achieve the tuning.

The inductors in series with the coupled inductor array are all set to -50 pH. This allows us to tune the resonator frequency positive and negative without violating the coupling coefficient equation, which requires the coupled inductors to be positive. So with the offset, zero resonator tuning is +50 pH in the coupled inductor array. The series inductor at the input is a dummy element required by our equal ripple filter optimizer [3].

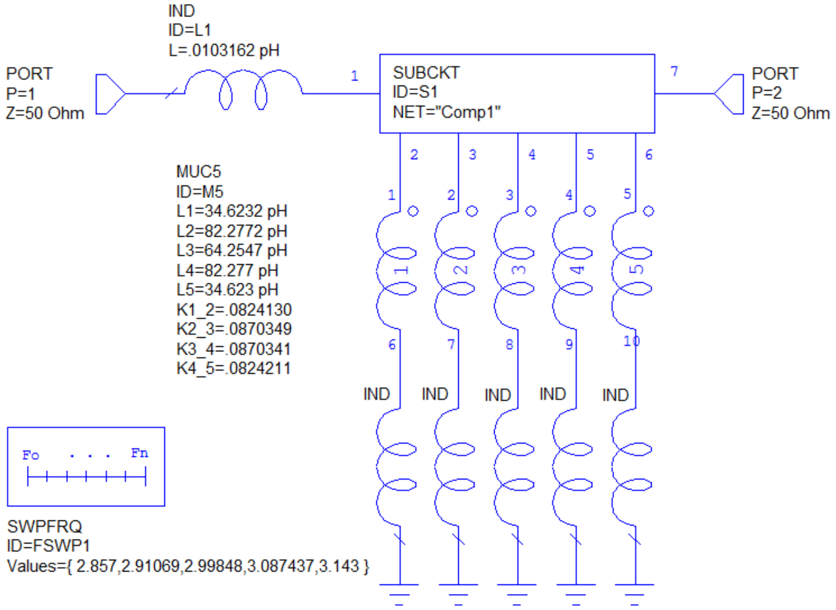


Figure 5. Port tuning schematic in Microwave Office.

The first iteration port tuned response is shown in Figure 6. The tunings in Figure 5 give us the magnitude and direction of the corrections we need to make to the physical layout. The outer resonators want to be shorter and the inner resonators want to be longer (zero is +50 pH). The couplings all need to increase. Note the symmetry in the tunings.

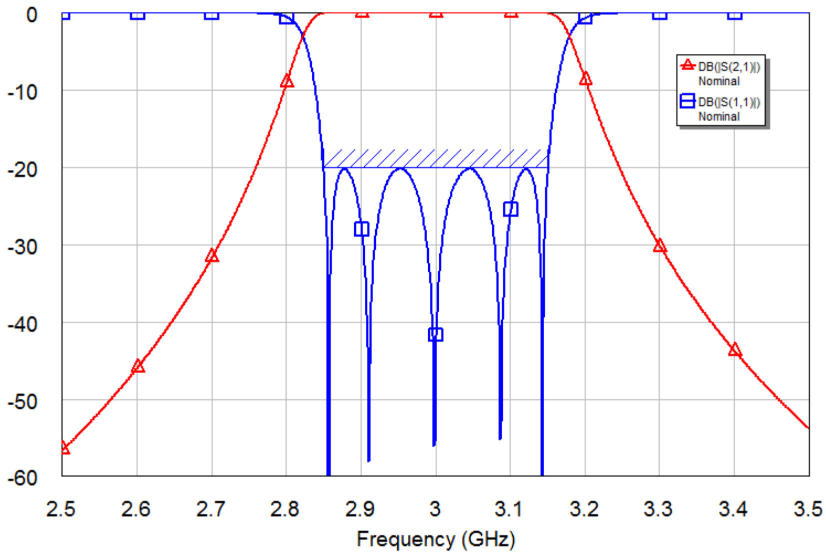


Figure 6. Port tuned initial layout.

So how do we relate our tunings to physical dimensions? In a closed box MoM simulator like Sonnet **em** or NI AWR EMSight we define our geometry on a uniform fixed grid, which is one by one mil in this case. So we can fine tune frequency by adding or subtracting one by one mil cells at the resonator open ends. And we can fine tune couplings by adding or subtracting one by one mil cells on the edges of the resonators in the gaps. We can determine the number of cells to add or subtract with simple linear interpolation.

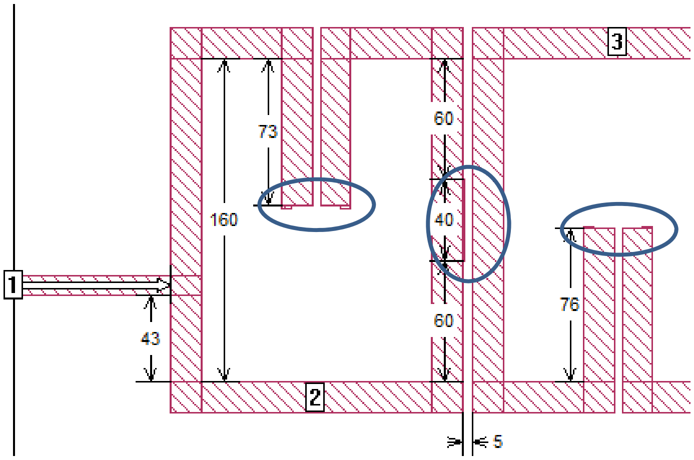


Figure 7. Delta tunes added to the first iteration nominal layout.

First we take our initial layout and add 10 cells of metal to the resonator open ends and we add 10 cells of metal to the strips we placed in the gaps, Figure 7. Next we port tune this new layout back to a perfect equal ripple response. We now have two sets of tunings with a delta of 10 cells between them. Next we compute a tuning sensitivity for the inductor tunes (pH / Cell) and a tuning sensitivity for the coupling tunes (K / Cell). Finally, we simply divide the nominal tunes by the sensitivities, Table 1. In the following iterations we used a delta of two cells. Convergence was achieved with only four iterations. The total number of EM simulations was 8 and the solution time for each simulation was 2 min. The complete record of the optimization can found in Appendix A.

	Delta (Cells)	Nominal Ind Tunes (pH)	Nom + Delta Ind Tunes (pH)	Sensitivity pH / Cell	Correction Cells
Reso1	10	34.6232	29.9224	0.47008	-33
Reso2	10	82.2772	77.3999	0.48773	66
Reso3	10	64.2547	60.2721	0.39826	36
Reso4	10	82.277	77.4003	0.48767	66
Reso5	10	34.623	29.9414	0.46816	-33

	Delta (Cells)	Nominal Coupling Tunes	Nom + Delta Coupling Tunes	Sensitivity K / Cell	Correction Cells
K1_2	10	0.082413	0.0425724	0.00398406	21
K2_3	10	0.0870349	0.0557054	0.00313295	28
K3_4	10	0.0870341	0.055705	0.00313291	28
K4_5	10	0.0824211	0.0425902	0.00398309	21

Table 1. Computation of corrections for the first iteration.

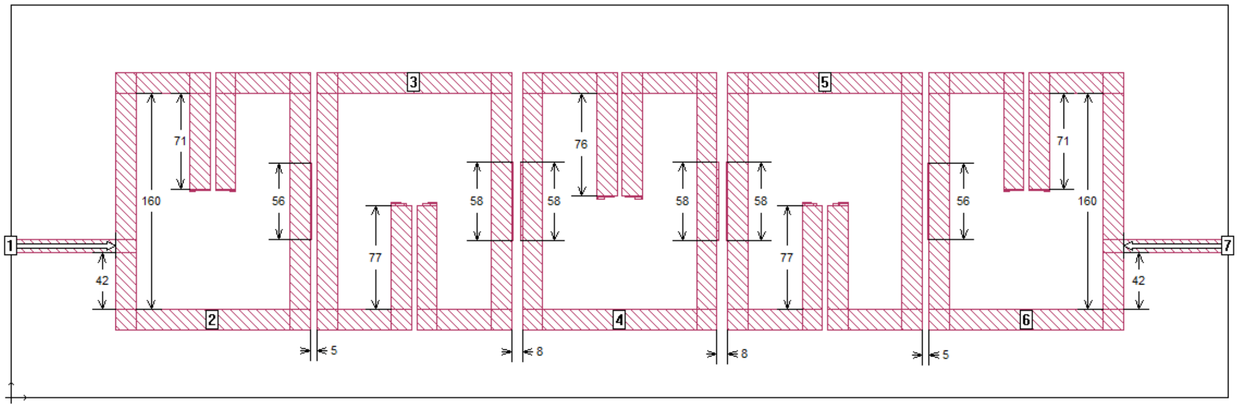


Figure 8. Final filter layout.

The final filter layout is shown in Figure 8. Typical thin-film etch tolerance is 0.1 mil, so we fully expect that the small features that we have defined will be accurately realized. We have applied this tuning technique to various planar topologies in X-band and Ku-band with excellent results. A good test to perform at this point is to remove the tuning ports and analyze the layout as a two port. The two port lossless simulation is shown in Figure 9.

A key advantage of our equal ripple optimizer is that it controls the filter bandwidth exactly in the lossless model. This becomes critical in contiguous multiplexer design. Also note there are no specifications in the stopband. Once we find an equal ripple transfer function in the passband the solution is unique. We can only modify the stopband by adding resonators or finite transmission zeros.

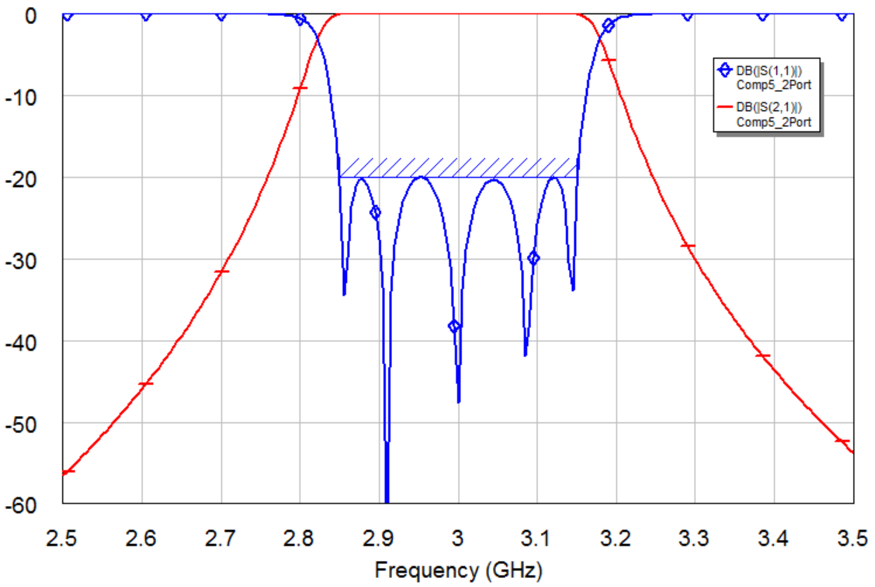


Figure 9. Two port simulation of final layout with no loss.

The two port simulation of the final layout with loss and metal thickness is shown in Figure 10. The bandwidth has expanded by a few MHz and there may be a small center frequency shift. It is interesting to note that in general, the influence of loss and metal thickness tend to compensate one another. In other words, if you apply them to your design one at a time, the results first shift in one direction and then shift back very close to the starting point.

We should also note that a lossless simulation of our filter takes about two minutes using a two computer cluster with 24 cores each (we are solving two frequencies in parallel). The simulation of the same filter with loss and metal thickness takes 12 minutes using the same cluster. So it is clearly more efficient to do most of our work in lossless mode then add loss and metal thickness at the very end.

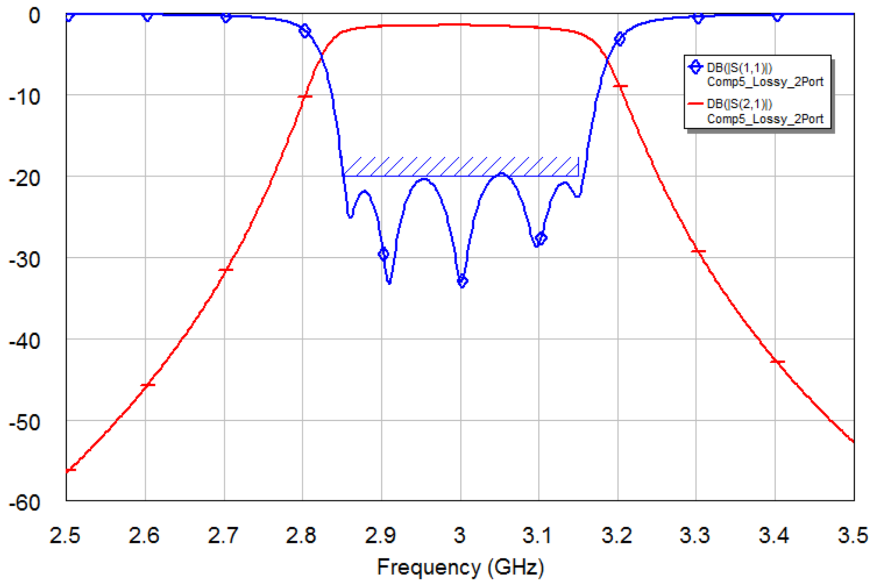


Figure 10. Two port simulation of the final layout with loss and metal thickness.

In conclusion we should point out that this design flow scales very well with filter order and number of ports. No matter what the filter order we can derive all the tuning sensitivities with only two EM simulations. We have applied this tuning method to cavity combline filters using FEM simulation with equally good results.

The ultimate stopband rejection we achieve with a microstrip filter is a combination of the filter response in the stopband and the isolation provided by the below cutoff waveguide channel that surrounds the filter. A distributed microwave filter comprised of quarter-wave or half-wave resonators tends to radiate at the open ends. In a waveguide channel, the microstrip resonators couple to evanescent modes in the channel and the filter response is modified [4]. Figure 11 shows the measured response of a microstrip interdigital filter in a housing with the cover on and off [1,2]. Again, the dramatic shift in response is not due impedance changes (the cover is too far away) but rather the coupling to the waveguide channel. You can put a metal paper clip or a coarse metal screen across the open channel and the response will shift back towards the full cover state.

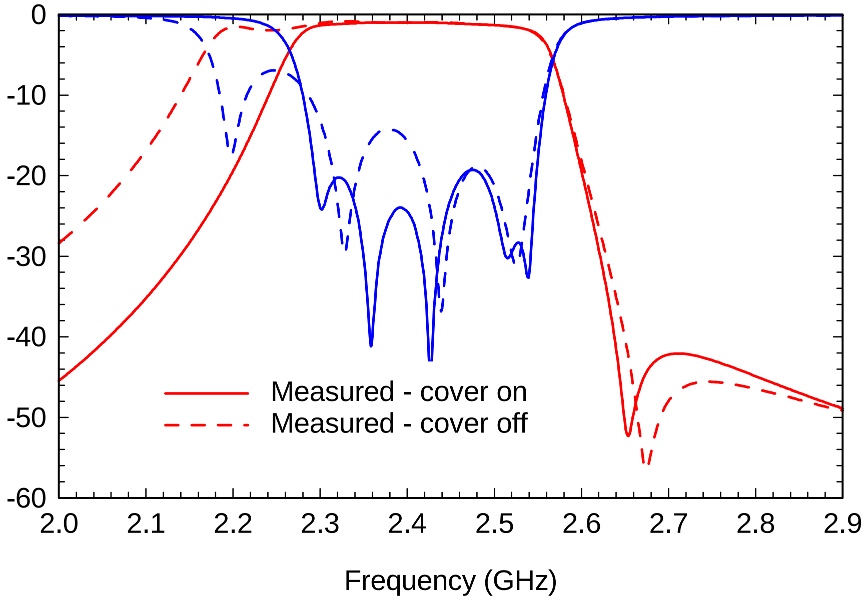


Figure 11. Microstrip interdigital filter measured with cover on and cover off.

Figure 12 shows a microstrip combline filter designed in NI AWR EMSight using our cell by cell tuning technique. We used the same design goals found in [1]. We also simulated the final design in NI AWR AXIEM. The two simulations are shown in Figure 13. There is clearly a large difference between the closed box MoM and the laterally open MoM simulations. We have measured versus modeled data for similar microstrip combline filters at X-band that show excellent correlation. Thus our confidence in the closed box MoM design approach is quite high.

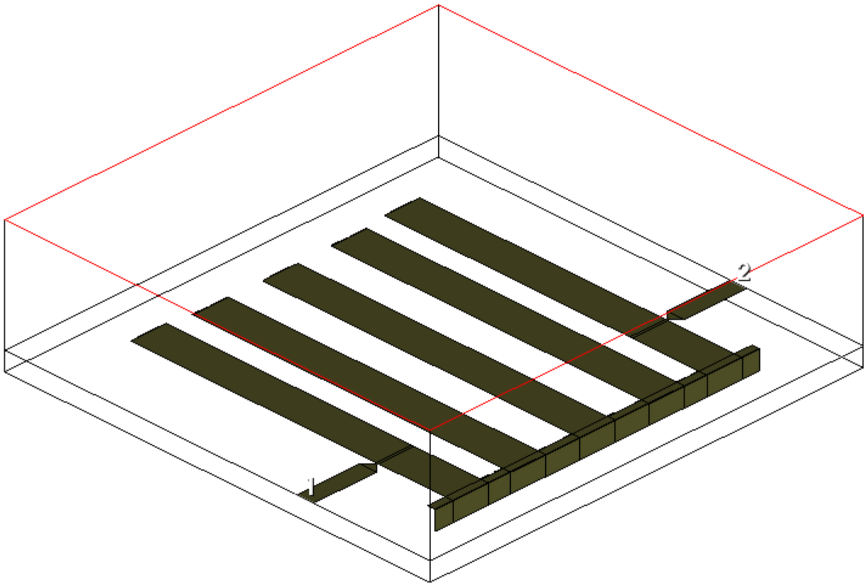


Figure 12. Microstrip combline filter designed in EMSight.

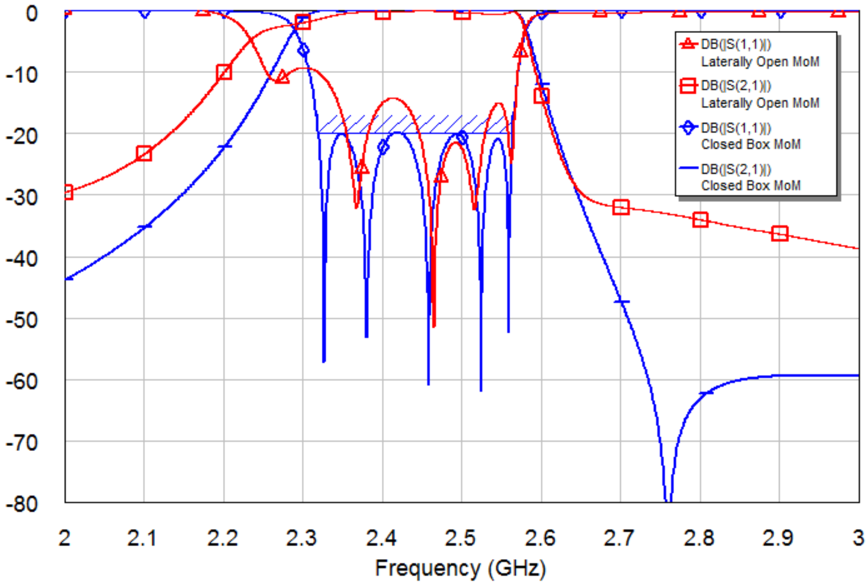


Figure 13. Microstrip combline filter designed in EMSight and simulated in AXIEM.

Probably a more interesting and fair comparison is to design the N=5 microstrip combline in both AXIEM and EMSight. Figure 14 compares to the two final designs. Both tools are indeed capable of designing a useful filter given their respective boundary conditions. The AXIEM dimensions were optimized to the nearest 0.1 mil. The EMSight design uses a 1 mil grid and the patch tuning technique described earlier. As we would expect, the filter in the waveguide channel has more rejection in the stopbands and the transmission zero position is different for the two filters. In Table 2 we report the final major dimensions for the two designs. These are clearly two unique designs and we cannot arbitrarily apply different boundary conditions when we use these filters in our system.

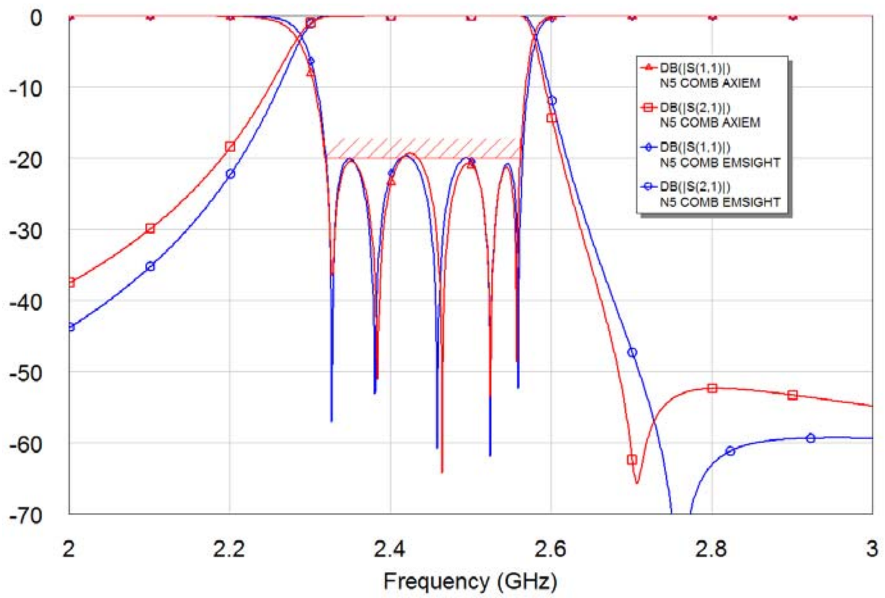


Figure 14. Microstrip combline filters designed in both AXIEM and EMSight.

Major Dimension	AXIEM	EMSight
Reso 1 Len	435.3	444
Reso 2 Len	432.2	439
Reso 3 Len	431.1	437
Gap 1	41.2	31
Gap 2	62.2	49
Tap Height	78.0	94

Table 2. Major dimensions for the AXIEM and EMSight designs. Units are mils

Figure 15 shows a microstrip tapped edge coupled filter centered at 16 GHz. It was designed in Sonnet **em** using the cell by cell tuning technique. We also simulated the final design using NI AWR AXIEM. The results are shown in Figure 16. Once again there is clearly a large difference in the closed box and laterally open MoM simulations. In the Sonnet **em** simulation, the transmission zero closest to the passband on the high side is due to a capacitive cross-coupling between resonators three and five. The transmission zero on the low side is due to a coupling from source to load in the waveguide channel. We see a similar zero appear in a conventional edge coupled filter when the waveguide channel is too wide [5]. The other high side transmission zero is actually two zeros at the same frequency due to the open stubs from the tap points towards the source and load. Given the results in Figure 14 we are confident that the edge coupled filter could be redesigned for the laterally open environment, if that was the desired boundary condition for the filter in the system.

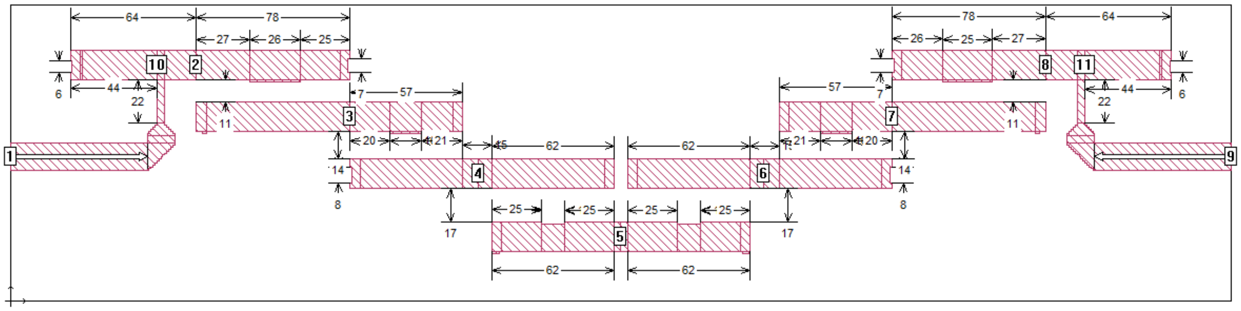


Figure 15. Microstrip tapped edge coupled filter designed using Sonnet **em**.

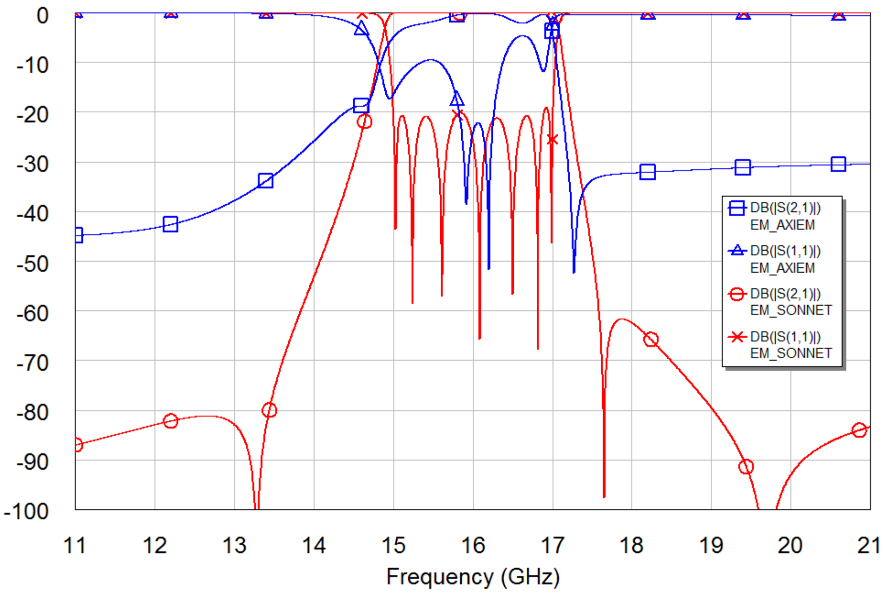


Figure 16. Microstrip tapped edge coupled filter designed in Sonnet **em** and simulated in AXIEM.

With all of the above in mind, we believe that in most cases microstrip filter design requires a closed box MoM simulator like Sonnet **em** or NI AWR EMSight. Laterally open MoM simlators like Keysight Momentum or NI AWR AXIEM lack the ability to model the waveguide channel correctly. Adding via metal to form side walls does not work for laterally open simulators. And adding via metal to form interior isolation walls also does not work in a closed box simulator.

Purely out of curiosity we simulated our final design for the microstrip folded hairpin filter using EMSight and AXIEM, Figure 17. To our great surprise the two simulations are quite close to each other.

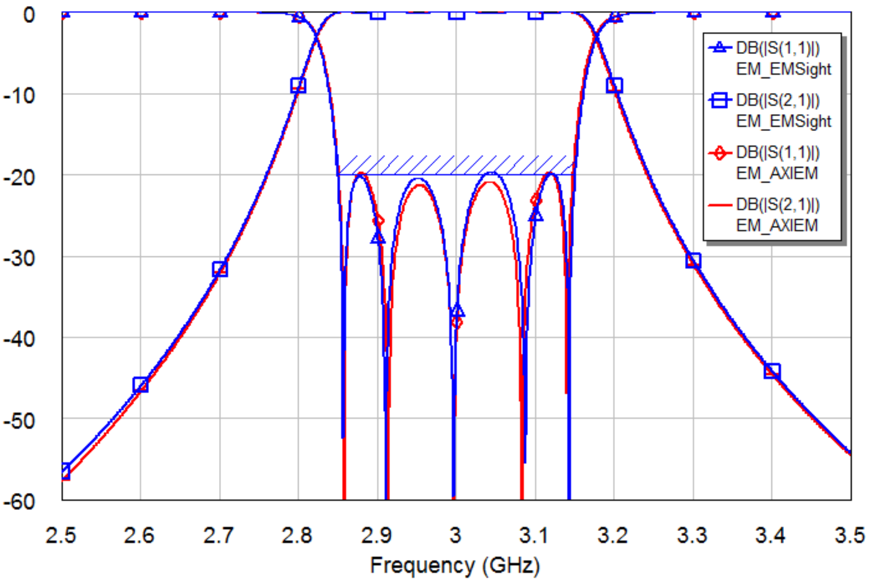


Figure 17. Simulation of N=5 folded hairpin filter using AXIEM and EMSight.

So what is different about the folded hairpin filter? The fields at the resonator open ends are 180 degrees out of phase and physically very close to each other. Our theory is that the fields cancel, there is very little radiation and therefore very little coupling to the waveguide channel. If this is true, the Qu for this topology may be higher than other distributed topologies because the losses in the housing walls will be lower. The microstrip folded hairpin filter is one of the few, or perhaps the only distributed filter topology that might be modeled with either a laterally open or closed box MoM simulator. To our knowledge this has never been reported in the open literature.

A microstrip hairpin filter at 94 GHz has been recently reported [6]. The design and measurement are perfectly valid because they were both performed with laterally open boundary conditions and no cover. If this filter is dropped into a channelized environment the results may be different, or they may demonstrate the same insensitivity to simulation method seen in Figure 17.

It is always tempting to apply a laterally open MoM simulator to microstrip filter design because it does not use a fixed grid and therefore has infinite geometrical resolution. While the fixed grid used in closed box MoM simulators at first seems to be a severe limitation for high resolution microstrip filter optimization, it can be overcome using the simple cell by cell technique demonstrated here.

References

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

[2] D. G. Swanson, Jr., “Corrections to “Narrow-Band Microwave Filter Design,” *IEEE Microwave Magazine*, vol. 9, no. 1, p. 116, Feb. 2008.

[3] EQR_OPT_MWO www.dgsboulder.com

[4] G. Matthaei, J. Rautio, and B. Willemsen, “Concerning the Influence of Housing Dimensions on the Response and Design of Microstrip Filters with Parallel-Line Couplings,” *IEEE Trans. Microwave Theory Tech.*, vol. MTT-48, pp. 1361-1368, August 2000.

[5] J.-S. Hong, *Microstrip Filters for RF/Microwave Applications*, Second Edition, p. 132, John Wiley & Sons, New York, 2011.

[6] http://www.awrcorp.com/sites/default/files/content/attachments/SS-M-DST-MC-2018.4.16.pdf

Appendix A

N5 HAIRPIN FILTER

Start Point Units are cells, pH and unit less for K

	Ind Tunes (pH)	Plus Offset (pH)	Offset Inductance
Reso1	34.6232	-15.3768	-50
Reso2	82.2772	32.2772	
Reso3	64.2547	14.2547	
Reso4	82.277	32.277	
Reso5	34.623	-15.377	

	Coupling Tunes
K1_2	0.082413
K2_3	0.0870349
K3_4	0.0870341
K4_5	0.0824211

Tap Height 43 mils

Iteration 1

	Delta (Cells)	Nominal Ind Tunes (pH)	Nom + Delta Ind Tunes (pH)	Sensitivity pH / Cell	Correction Cells
Reso1	10	34.6232	29.9224	0.47008	-33
Reso2	10	82.2772	77.3999	0.48773	66
Reso3	10	64.2547	60.2721	0.39826	36
Reso4	10	82.277	77.4003	0.48767	66
Reso5	10	34.623	29.9414	0.46816	-33

	Delta (Cells)	Nominal Coupling Tunes	Nom + Delta Coupling Tunes	Sensitivity K / Cell	Correction Cells
K1_2	10	0.082413	0.0425724	0.00398406	21
K2_3	10	0.0870349	0.0557054	0.00313295	28
K3_4	10	0.0870341	0.055705	0.00313291	28
K4_5	10	0.0824211	0.0425902	0.00398309	21

Tap Height 43 mils

Iteration 2 Stop and move tap

	Delta (Cells)	Nominal Ind Tunes (pH)	Nom + Delta Ind Tunes (pH)	Sensitivity pH / Cell	Correction Cells
Reso1		57.4139			
Reso2		46.3458			
Reso3		47.8912			
Reso4		46.3457			
Reso5		57.4189			

	Delta (Cells)	Nominal Coupling Tunes	Nom + Delta Coupling Tunes
K1_2		0.077704	
K2_3		0.0254762	
K3_4		0.0254744	
K4_5		0.0777069	

Tap Height 43 mils

Iteration 3 Moved tap down one mil

	Delta (Cells)	Nominal Ind Tunes (pH)	Nom + Delta Ind Tunes (pH)	Sensitivity pH / Cell	Correction Cells
Reso1	2	58.2371	56.8642	0.68645	12
Reso2	2	45.9197	45.2862	0.31675	-13
Reso3	2	47.7609	47.3075	0.2267	-10
Reso4	2	45.9198	45.2862	0.3168	-13
Reso5	2	58.2418	56.8628	0.6895	12

	Delta (Cells)	Nominal Coupling Tunes	Nom + Delta Coupling Tunes	Sensitivity K / Cell	Correction Cells
K1_2	2	0.0339788	0.0242766	0.0048511	7
K2_3	2	0.00390846	-0.00707611	0.005492285	1
K3_4	2	0.0039075	-0.00707515	0.005491325	1
K4_5	2	0.0339868	0.024273	0.0048569	7

Tap Height 42 mils

Iteration 4

	Delta (Cells)	Nominal Ind Tunes (pH)	Nom + Delta Ind Tunes (pH)	Sensitivity pH / Cell	Correction Cells
Reso1	2	49.6141	49.0317	0.2912	-1
Reso2	2	57.0471	56.0049	0.5211	14
Reso3	2	56.4569	55.2344	0.61125	11
Reso4	2	57.0474	56.0049	0.52125	14
Reso5	2	49.6173	49.0299	0.2937	-1

	Delta (Cells)	Nominal Coupling Tunes	Nom + Delta Coupling Tunes	Sensitivity K / Cell	Correction Cells
K1_2	2	-0.00808651	-0.0159862	0.003949845	-2
K2_3	2	-0.00520939	-0.013861	0.004325805	-1
K3_4	2	-0.00521054	-0.0138615	0.00432548	-1
K4_5	2	-0.00805399	-0.015989	0.003967505	-2

Tap Height 42 mils

Final Sim

	Ind Tunes (pH)
Reso1	49.5047
Reso2	49.2421
Reso3	49.6736
Reso4	49.2545
Reso5	49.5025

Zero tuning
is +50 pH

	Coupling Tunes
K1_2	-0.00466811
K2_3	-0.00570387
K3_4	-0.00570258
K4_5	-0.00466675

Tap Height 42 mils

Appendix B

There is at least one alternative to port placement for the folded hairpin filter. Some users may feel more comfortable placing ports in the center of coupled region as shown in Figure 1. Port 2 and Port 11 are dummies in some sense, but they make the tuning sensitivities for the inductors and the couplings more uniform across the filter. The simulation time needed to calibrate ports is finite, so adding ports does add to the total simulation time. The Microwave Office schematic for the port tuning is shown in Figure 2.

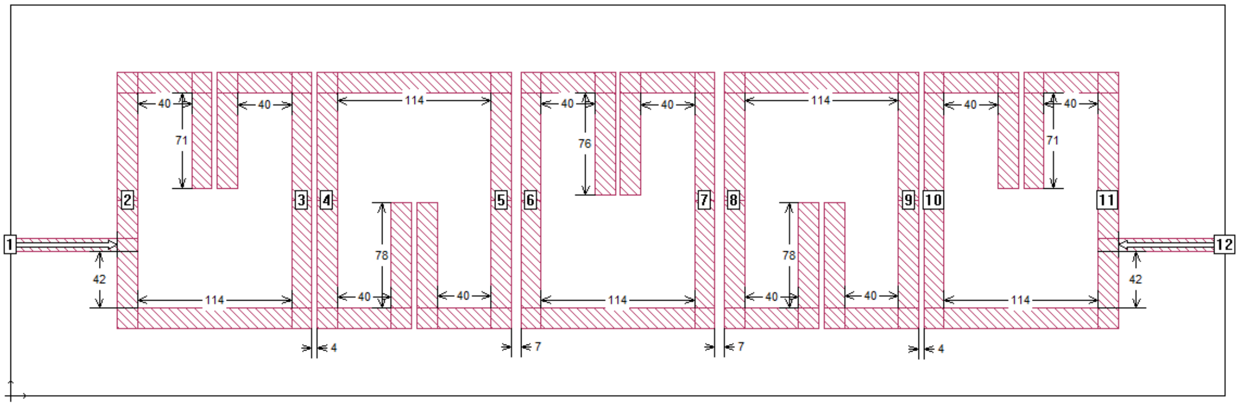


Figure 1. An alternative port tuning scheme for the folded hairpin filter.

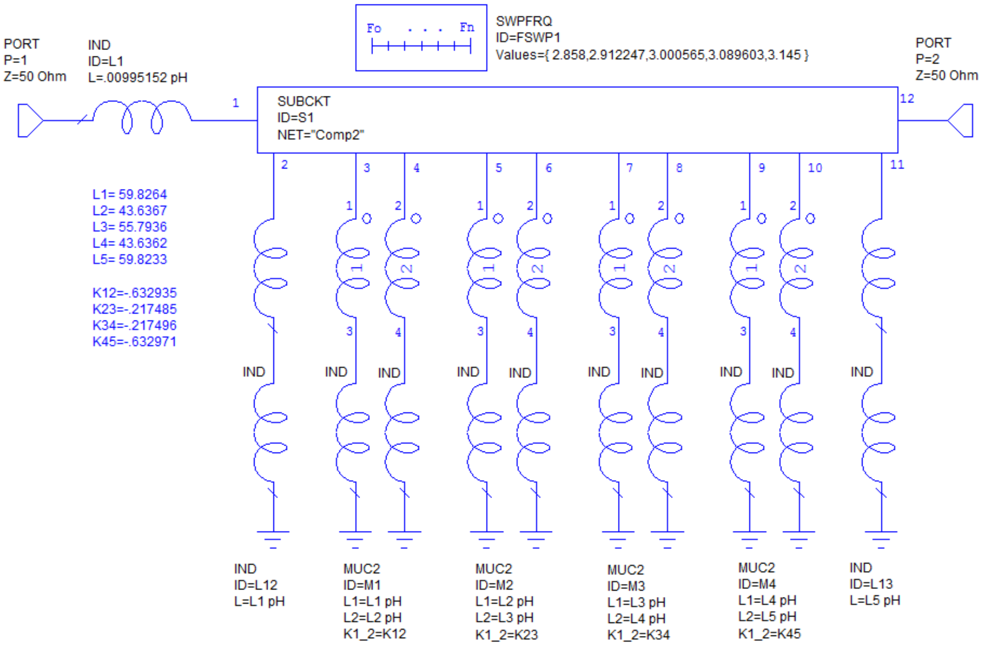


Figure 2. Microwave Office port tuning schematic for the layout in Figure 1.