Fast Analysis and Optimization of Combline Filters Using FEM

Daniel G. Swanson, Jr. and Robert J. Wenzel*

Bartley R.F. Systems Inc., Amesbury, MA 01913
*Wenzel / Erlinger Associates, a Subsidiary of Bartley R.F. Systems Inc., Agoura Hills, CA 91301

***Abstract* — We analyze a combline filter using the Finite Element Method (FEM) with ports where the tuning screws would normally be. The filter is tuned with a circuit simulator using the multiport S-parameter data and lumped capacitors at the ports. We can then optimize the combline filter very rapidly by mapping the "coarse" circuit model to the "fine" FEM model. This optimization is shown to converge in one iteration, with a good starting point.**

I. INTRODUCTION

Analysis and optimization of filter circuits using electromagnetic field-solvers has been evolving steadily over the last decade. Many different strategies have been developed for including a field-solver in the optimization loop. The most simple, but least elegant approach uses a full electromagnetic analysis for every gradient computation required by the optimizer. If the circuit can be subdivided, individual pieces of the circuit can be computed and updated during optimization, with considerable savings in computation time. A more elegant approach establishes a connection or mapping between a circuit theory based model and full em analysis of the circuit [1]-[5]. The circuit theory model is sometimes called the "coarse model" because it captures the basic behavior of the circuit but ignores more subtle aspects, like parasitic couplings. The field-solver solution then becomes the "fine model" which captures the entire physics of the problem, but takes much longer to compute.

II. THE COARSE MODEL

For the combline filters we will study, the coarse model is generated by the program CLD [6]. The circuit model (Fig. 1) is in cascade form and includes the input tap model due to Cristal [7]. Transmission line resonators are converted to physical dimensions using the data from Cristal [8] and an equal diameter rod solution is found using the procedure in Wenzel [9]. An empirical correction factor is applied to the rod spacings to account for the well-known bandwidth expansion problem in combline filters. We know from experience that the largest errors in a design generated by CLD are in the tap position and the first and last gaps between rods.

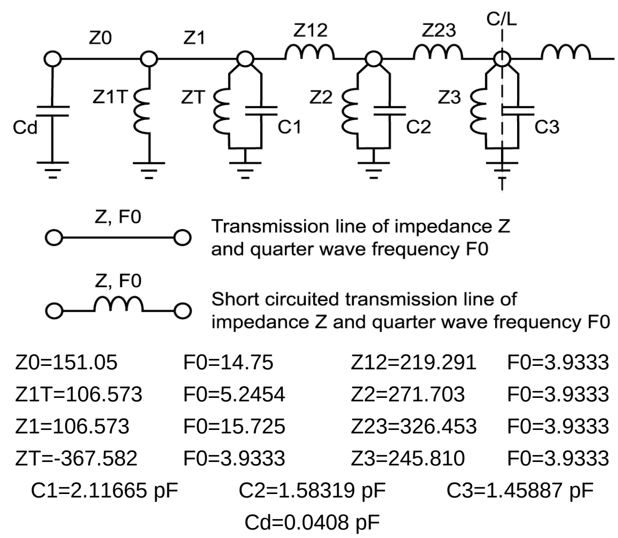

Fig. 1. Combline tapped line cascade equivalent circuit from Cristal [2]. Element values are for the N=5 experimental hardware. The 21 dB equal ripple bandwidth is 1.178 to 1.814 GHz.

III. THE FINE MODEL

The physical realization of the circuit model in Fig.1 is shown in Fig. 2. The geometry shown was analyzed with Agilent HFSS [10] and Ansoft HFSS [11]. Both programs are based on the Finite Element Method (FEM), which is well suited for the analysis of this filter topology. The results obtained with both programs were equivalent, although there were some differences in how the problem must be specified. The geometry generated by CLD can be entered into the field-solver with as much resolution as the user desires. All pertinent mechanical details, such as finite radii can be included. We could analyze the filter as a two port and adjust the tuning screws and the rod spacings for equal ripple performance. However, this is not particularly efficient and for higher order filters or a multiplexer the computation time would be prohibitive.

In the case of the combline filter, at least part of the resonator tuning structure can be modeled as a simple lumped capacitor. With this in mind, we turn our 2-port field-solver model into a 7-port (Fig. 3) by forming ports at the ends of the resonator rods within the re-entrant cover. The field-solver model is computed at a few frequencies across the band of interest and the 7-port data is exported to a linear simulator where we add lumped capacitors to the resonator ports.

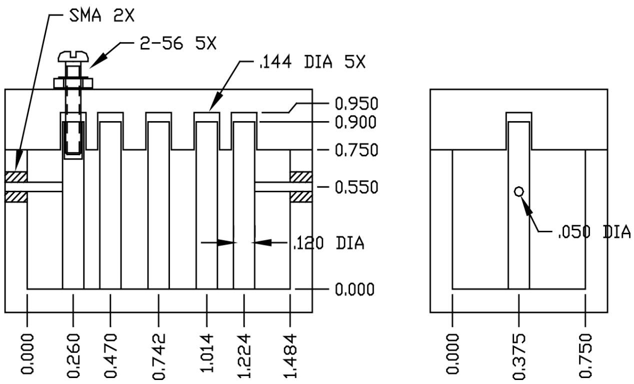

Fig. 2. Dimensions (inches) of the N=5 tapped combline experimental hardware. The tap position for the CLD design was 0.562 inch. The as built tap position was 0.550 inch.

Only a few frequencies need to be computed on the field-solver because the 7-port structure by itself is no longer resonant and the circuit simulator can interpolate the S-parameter data. We can now tune the field-solver model quite rapidly using the linear simulator. For the combline topology, small corrections to the coupling between resonators can be achieved by adding series, short-circuited transmission lines between the resonator ports. Positive impedance implies that coupling increases, while negative impedance implies that coupling decreases.

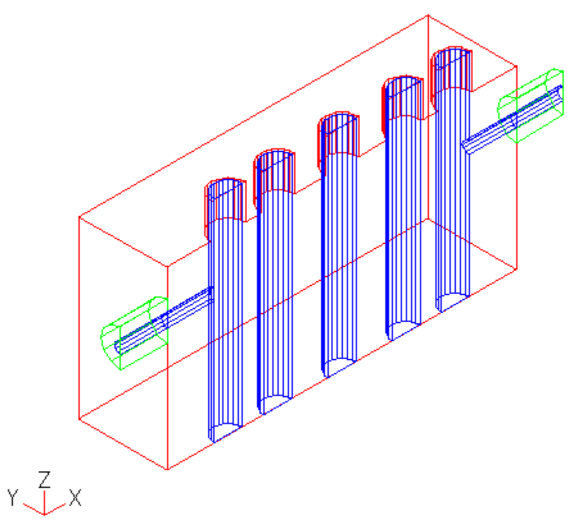

Fig. 3. HFSS model of the tapped combline filter. The resonator ends are modified to create ports at each resonator. A symmetry plane has been applied down the center of the structure.

IV. Tapped Combline Example

The tapped combline geometry in Fig. 2 was analyzed as a 7-port network (Fig. 3) using Agilent HFSS. The original geometry is truncated at the ends of the resonator rods. Thus, there are low impedance ports at the ends of each resonator. However, the essential nature of the filter has not been modified. We are assuming that the actual filter will be tuned with screws, but we are not trying to compute the exact geometry of the tuning screws. The problem was meshed at 2 GHz and the fast sweep option was invoked for an analysis from 100 MHz to 8 GHz. The total solution time on an 850 MHz Pentium PC was 13 min.

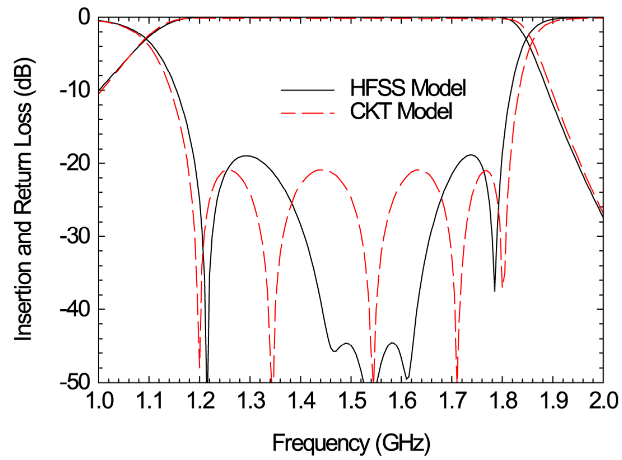

Fig. 4. HFSS analysis compared to circuit model for the original geometry generated by CLD. Tap position is 0.562 inch.

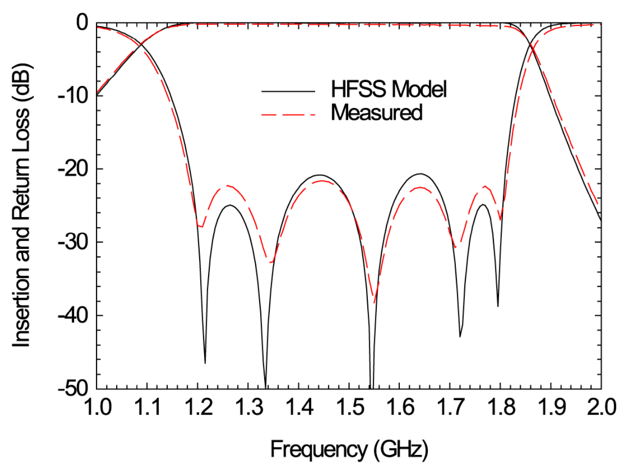

Fig. 5. HFSS analysis compared to experimental hardware. Tap position is 0.550 inch.

The original CLD design called for a tap position of 0.562 inch from the bottom of the cavity. Fig. 4 shows the HFSS analysis for this tap position compared to the circuit model for the same geometry. The HFSS analysis indicates

0-7803-6540-2/01/$10.00 (C) 2001 IEEE

that the tap position is incorrect and there may be other errors as well. We did have measured data and tuning information from experimental hardware built to these dimensions fifteen years ago. Based on this information and our knowledge of tapped combline behavior, we moved the tap position down 0.012 inch and built new experimental hardware.

Fig. 5 shows the measured data for the new experimental hardware (Fig. 2) and the HFSS analysis for the same dimensions. The agreement between the two is quite good although there are still some small errors. The bandwidth of the HFSS analysis is slightly narrow, a characteristic of CLD designs that allows for consistent correction with coupling screws. We left the tapped combline at this point and did not attempt to fully correct all the errors in the design.

V. Filters With Combline And Interdigital Inputs

Next, we designed combline filters with interdigital redundant rod inputs and combline redundant rod inputs. These designs were needed for a study of the stopband behavior of combline filters with different input coupling structures [12]. After our success with the tapped combline, we also wondered if it was possible to develop a simple procedure that would fully correct the initial design using the field-solver data.

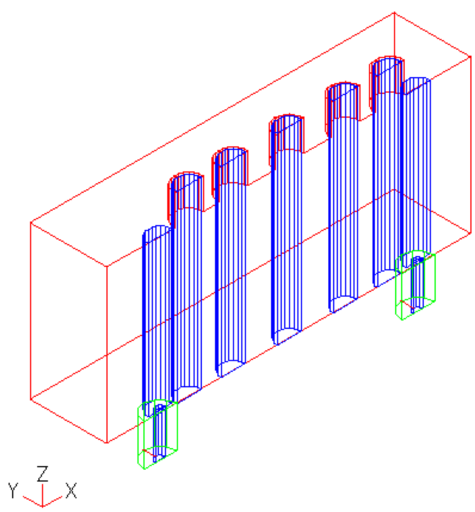

Fig. 6. HFSS model of the combline filter with redundant interdigital rod input.

A filter with interdigital rod input was designed using the same techniques described in Section II and the HFSS model for this design is shown in Fig. 6. The HFSS analysis is compared to the circuit model in Fig. 7. We then re-optimized the circuit model to match the field-solver data and examined the deltas in the dimensions between the two solutions. The HFSS model is then corrected by applying the computed deltas in the same direction. This very basic correction procedure is often the first step in more sophisticated optimization procedures. The deltas and corrections are shown in Table 1.

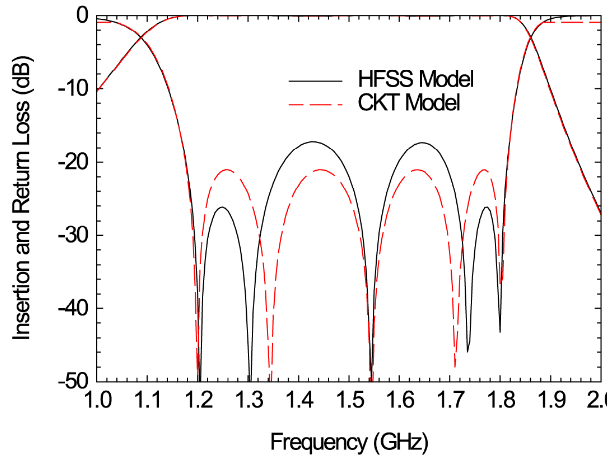

Fig. 7. HFSS model and circuit model for the original design of interdigital rod input filter.

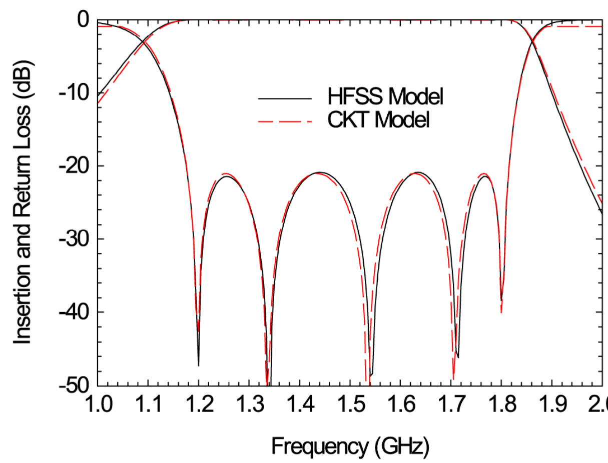

Fig. 8. Corrected HFSS model and original circuit model for interdigital rod input filter.

TABLE I
Spacings Between Rods - Interdigital Input

	Original (inches)	Fit to FEM (inches)	Delta Orig - Fit	Percent Change
S12	.0221	.0232	-.0011	-4.9
S23	.0959	.0950	+.0009	+0.9
S34	.1552	.1567	-.0015	-1.0

In Table I a negative delta implies that the spacing should be decreased, positive delta implies an increase. Note that the largest percentage error is in the first spacing, similar to the tap position error in the tapped combline.

The central gaps are one percent too big (bandwidth slightly narrow) and the spacing between resonators one and two is one percent too small. If we assume that coupling screws will be used, we would like all the spacings to be slightly too big so the screws will be effective. All of these observations are consistent with experimental hardware built over the last thirty years.

A filter with redundant combline rod input was also designed. The same design and correction procedures described above were used. The HFSS model for this filter is shown in Fig. 9 and Table II contains the optimization data.

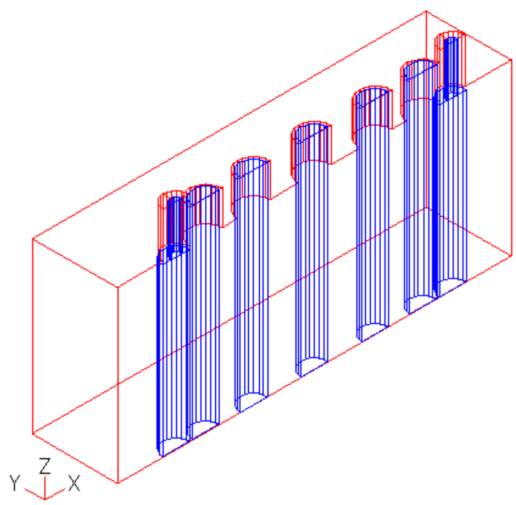

Fig. 9. HFSS model of redundant combline rod input filter.

TABLE II
SPACINGS BETWEEN RODS - COMBLINE INPUT

	Original (inches)	Fit to FEM (inches)	Delta Orig - Fit	Percent Change
S12	.0106	.0111	-.0005	-4.8
S23	.0899	.0880	+.0019	+2.1
S34	.1512	.1526	-.0014	-0.9

The errors and corrections required for the combline input rod case are very similar to interdigital input rod case. Although we do not have experimental hardware for these last two designs, the field-solver results for the tapped combline case give us confidence that these results are correct as well. The fact that these results are consistent with observed tuning behavior for many filters also gives us confidence.

For these last two examples, a second field-solver run was made to confirm the accuracy of the corrected dimensions. Once we are confident that this procedure is correct, the second FEM analysis is actually not needed and the optimization is complete with only one, fast electromagnetics based analysis.

VI. CONCLUSION

We have outlined an analysis and optimization procedure for combline filters that uses the coarse / fine model concept and commercial FEM simulators. By placing ports at the tuning screw locations we obtain S-parameter data for the entire filter that can be tuned using lumped capacitors in a circuit simulator. This approach to filter tuning on the computer eliminates the need for an electromagnetic analysis every time a small change in tuning geometry is made. As in any optimization procedure, the convergence behavior depends strongly on the quality of the starting point. In this case, the coarse circuit model is indeed quite good and the field-solver is only needed to correct errors in dimension of five percent or less.

REFERENCES

[1] J. W. Bandler, S. Ye, R. M. Biernacki, S. H. Chen and D. G. Swanson, Jr., "Minimax microstrip filter design using direct em field simulation, *1993 IEEE MTT-S Int. Microwave Symp. Dig.*, vol. 2, pp. 889-892, June 1993.

[2] J. W. Bandler, R. M. Biernacki, S. H. Chen, D. G. Swanson, Jr. and S. Ye, "Microstrip filter design using direct em field simulation, *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-42, no. 7, pp. 1353-1359, July 1994.

[3] J. W. Bandler, R. M. Biernacki, S. H. Chen, P. A. Grobelny and R. H. Hemmers, "Space mapping technique for electromagnetic optimization," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-42, no. 12, pp. 2536-2544, December 1994.

[4] A. M. Pavio, "The electromagnetic analysis and optimization of a broad class of problems using companion models," *1995 IEEE MTT-S Int. Microwave Symp., Workshop WMFE*, May 1995.

[5] J. W. Bandler, R. M. Biernacki, S. H. Chen and Y. F. Huang, "Design optimization of interdigital filters using aggressive space mapping and decomposition," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-45, no. 5, pp. 761-769, May 1997.

[6] CLD – Combline Design Ver. 3.0, Bartley R.F. Systems, Amesbury, MA.

[7] E. G. Cristal, "Tapped-line coupled transmission lines with applications to interdigital and combline filters," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-23, no. 12, pp. 1007-1012, December 1975.

[8] E. G. Cristal, "Coupled circular cylindrical rods between parallel ground planes," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-12, no. 4, pp. 428-439, July 1964.

[9] R. J. Wenzel, "Theoretical and practical application of capacitance matrix transformations to TEM network design," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-14, no. 12, pp. 635-647, December 1966.

[10] Agilent HFSS Ver. 5.6, Agilent EEsof EDA, Santa Rosa, CA.

[11] Ansoft HFSS Ver. 7.0, Ansoft Corporation, Pittsburgh, PA.

[12] R. J. Wenzel and D. G. Swanson, Jr., "Observations on the stopband performance of tapped line filters," *2001 IEEE MTT-S Int. Microwave Symp. Dig.*, May 2001.