Coaxial Filters Optimization Using Tuning Space Mapping in CST Studio

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Abstract. *This paper deals with the optimization of coaxial filters using Tuning Space Mapping (TSM) method implemented to CST environment. The function of fine and coarse model and their link between each other is explained. In addition, supporting macros programmed in VBA language, which are used for maximum efficiency of the optimization from the user's point of view, are mentioned. Macros are programmed in CST and are also used for automatic calibration constants determination and for automatic calibration process between the coarse model and the fine model. The whole algorithm is illustrated on the particular seven-order filter design and optimized results are compared to measured ones.*

Keywords

Tuning Space Mapping, optimization, fine model, coarse model, VBA language, CST.

1. Introduction

In the current rapid development of complex communication systems, the demand of the microwave filters becomes very critical. The structure of these filters is becoming more and more complex (diplexers, combiners etc.). With the development of such filters, there is a need to accurately design and model these filters. These days, in engineering practice, the EM simulators (CST, HFSS, etc.) used for the simulation and modeling of complex filters are commonly used. Nevertheless, these EM simulators are very CPU-intensive. The standard procedure of the microwave filter design is very complex and it involves the synthesis of the filter and the subsequent modeling in EM simulator. The design of the filter in EM simulator includes the modeling of separate sub-models of the filter (e.g. input/output coupling, internal coupling, etc.). After the sub-models are put together, the complete filter is created. This procedure is inaccurate because the filter design is created using separate models. These models do not respect the other parts of the filter in sufficient way. The consequence of this procedure in the ending phase is the fact that the response of the designed filter (the so-called laboratory sample) does not satisfy the specification in many cases. Then, there is a need to mechanically modify and tune the produced filter in a very complex way. This procedure is very long-lasting and mainly economically demanding. That is why the current trend is to develop such optimizing methods, which are able to optimize the complete filter model directly in CPU-intensive EM simulator and prevent the necessary mechanical modifications of laboratory sample accordingly.

2. Tuning Space Mapping

Tuning Space Mapping is a widely used method in microwave techniques for the optimization of so-called "fine" models (typically implemented with CPU-intensive EM simulators). In order to reduce computer time on one hand and keep very high accuracy of numerical model on the other, John W. Bandler introduced an algorithm which enables the optimization of the fine models without the need of direct optimization in EM simulator [1].

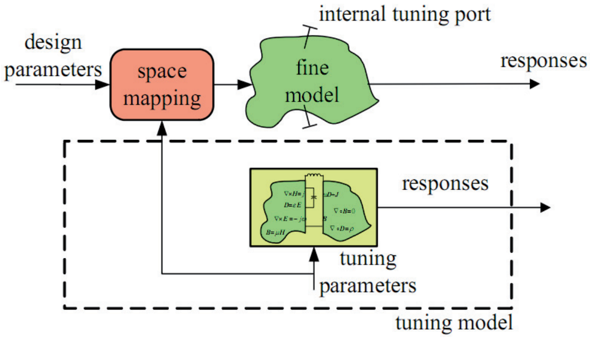


Fig. 1. The concept of tuning model [1].

TSM algorithm is based on the comparison of the so-called fine and coarse model. Coarse model (sometimes called tuning model) is constructed by introducing circuit-theory based components (e.g., capacitors, inductors or coupled-line models) into the fine models structure. The conceptual illustration of the tuning model is shown in Fig. 1. These circuit-theory based components introduced into the fine model structure with the help of discrete ports are used to tune the coarse model. The coarse model is then updated and optimized in each of the iterations. This process takes less CPU effort than the direct optimization of the fine model in EM simulator, because the coarse model is typically implemented in circuit simulator. Calibration process is needed to transform the optimal tuning parameters of the coarse model into an appropriate modification of the fine model variables. The calibration process involves auxiliary models. If it is possible, calibration process can be realized using analytical formulas. Entire algorithm is repeated until the fine model response is sufficiently close to the designed target. Coarse model structure as well as a proper selection of tuning elements usually requires significant engineering expertise.

3. TSM Implementation

TSM algorithm has been implemented into MWS and Design Studio (DS). MWS is used for a filter fine model implementation with discrete ports (Fig. 2). Discrete ports have negligible influence on filter response and they are used for connecting the tuning capacitors. Then the optimization of coarse model (Fig. 3.) is done in DS with the help of tuning capacitors.

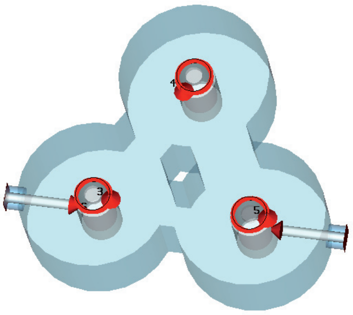


Fig. 2. The fine model of triplet in CST MWS.

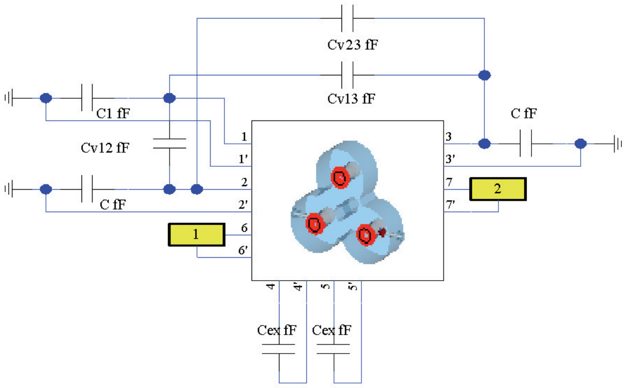


Fig. 3. The coarse model of triplet in CST DS.

In order to transform optimized values of capacitors to adequate changes of fine model parameters a calibration constant between both values has to be known. To do so the auxiliary models are needed. In Fig. 4 the fine model in MWS for relation definition between the iris width *W* and coupling coefficient *k* and a corresponding coarse model in DS for relation definition between coupling capacitor C_v and the coupling coefficient *k* of the same coupling is depicted. From the coefficient ratio of both relations a calibration constant of -1 fF per 0.745 mm can be deduced (Fig. 5, 6). This procedure is used for calibration constant deduction of all remaining variables (capacitive cross-coupling and external coupling).

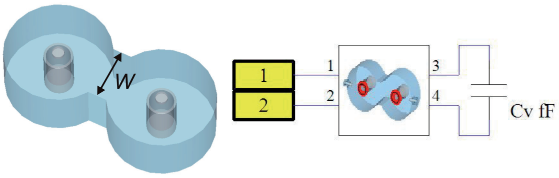


Fig. 4. The fine (left) and coarse (right) auxiliary model of inductive coupling.

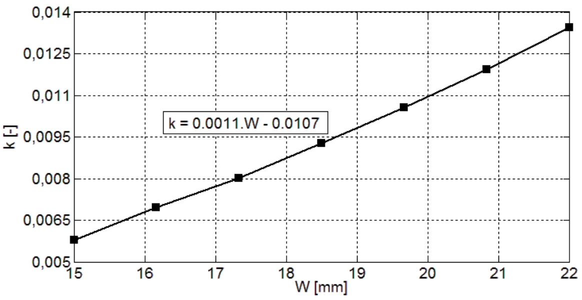


Fig. 5. Coupling coefficient in dependence on the iris width W.

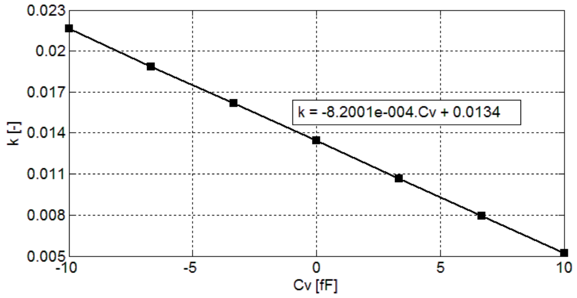


Fig. 6. Coupling coefficient in dependence on the coupling capacity *Cv*.

4. Supporting Macros

The only disadvantage of TSM is the needed manual calculation of calibration constants and manual transformation of the optimal values of tuning capacitors to the adequate changes of fine model parameters. This process is very time-consuming. The important fact is that the calibration constants have to be determined in each of TSM iterations from the current size of the fine model parameter. In the opposite case, the TSM algorithm will not converge successfully.

In order to make the TSM method in CST Studio maximally efficient, macros are used to significantly reduce the time which is needed for the tuning of coaxial cavity filters and n-plexers in general. These macros are created in CST with the help of VBA language and make the optimization process automatic from the user point of view in a maximal way. Altogether, the optimization process of four macros is available.

Fig. 7 depicts the diagram of the complete optimization flow in CST Studio using the TSM method and supporting macros. The first step of the optimization flow is the creation of necessary models (the coarse and fine model of the complete filter, auxiliary fine and coarse models). If all the needed models are available, the user chooses the desired parameters of the fine model of the filter, with which the user wants to tune the filter. The user executes the parametric sweep analysis of the chosen parameters with the help of auxiliary fine models and corresponding auxiliary coarse models. The results are saved to the special files using the created macros. That is how the needed source data, which will be needed later for the calibration constants definition and calibration process, will be prepared. The next step of the optimization is the calibration constants definition. For this purpose the macro with graphical user interface is used. The coarse model is then optimized in CST DS. The macro automatically performs the calibration process and starts the new simulation of the updated fine model. The whole optimization flow ends if the response of the fine model is sufficiently close to the design specification.

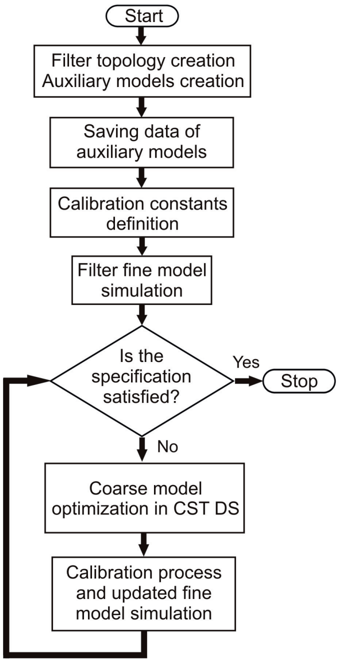


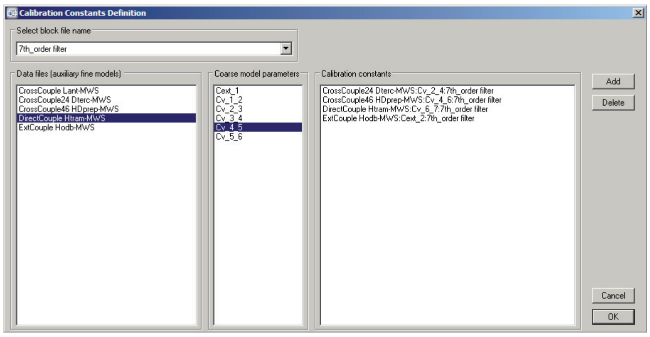
Fig. 7. Optimization flow.

4.1 Saving Data of Auxiliary Models

There has to be source data available in order to automatically determine calibration constants between optimal parameter values of the coarse and the fine model parameters. These data are reached by the auxiliary fine model parametric sweep analysis and by parametric sweep analysis of the coupling capacitor of the auxiliary coarse model for particular coupling. Macros (MWS and DS) save the results of the analysis to the file in a form of a table. It is sufficient to execute parametric sweep analysis for the small number of points, e.g. seven points. These values will be approximated in calibration process by 2-degree polynomial.

4.2 Calibration Constants Definition

Fig. 8 shows the graphical user interface of the macro. The user only creates the relevant relations between tuning capacitors of the coarse model and data of the auxiliary fine models saved by the previous macro.



Select block file name
7th_order filter

Data files (auxiliary fine models)
CrossCouple Lant-MWS
CrossCouple24 Dterc-MWS
CrossCouple46 HDprep-MWS
DirectCouple Htram-MWS
ExtCouple Hodb-MWS

Coarse model parameters
Cext_1
Cv_1_2
Cv_2_3
Cv_3_4
Cv_4_5
Cv_5_6

Calibration constants
CrossCouple24 Dterc-MWS:Cv_2_4:7th_order filter
CrossCouple46 HDprep-MWS:Cv_4_6:7th_order filter
DirectCouple Htram-MWS:Cv_6_7:7th_order filter
ExtCouple Hodb-MWS:Cext_2:7th_order filter

Fig. 8. Interface for calibration constants definition.

The handling of the macro graphical user interface is intuitive. Firstly, it is necessary to choose the file name of the block (MWSSCHEM or MWSPARA) which is the part of the coarse model in CST DS. Afterwards, the user has to choose the file name with the data from CST MWS in the window called *Data files (auxiliary fine models)*. After the choice of the coarse model parameter in the *Coarse model parameter* window, the calibration constant is created after clicking on the *Add* button. It is possible to delete calibration constant by clicking on its name and then click on the *Delete* button [2]. The calibration constants defined by the user are saved to the file in the form of relations between the tuning capacitors of the coarse model and parameters of the fine model.

4.3 Automatic Calibration Constants Determination and Automatic Calibration Process

Except for the possibility of pre-tuning with the help of Tune tool, the built-in optimizer is used for optimization in CST DS. Marco starts pre-set optimizer and afterwards it compares the reached goal function level with the value selected by the user in the optimizer and executes calibration process according to the result. If the reached value of the goal function level is smaller or equal to the set goal function level by the user, then the macro executes the calibration process with the help of defined calibration constants in the paragraph 4.2, and on the basis of the data according to the paragraph 4.1. The macro automatically starts the simulation of the updated model. On contrary, the calibration process will not be executed and the macro reports a message that the optimization was not successful. In order to get the detailed information regarding the result of optimization, there exists the possibility to see the optimizer logfile. After the calibration process is finished, the macro automatically sets the values of tuning capacitor to the zero value, for the easier pre-tuning of the filter by means of Tune tool in each of the following iterations. The macro makes sure in the safe way that the value of the fine model parameter is equal to zero during optimization. In such a case, the macro wants the user to check the parameter list of the fine model.

5. Seven-Order Filter Optimization

The seven-order filter has been designed and optimized using Tuning Space Mapping implemented into CST environment. The filter passband frequencies have been projected 409.5 - 430.5 MHz. The projected return loss is 20 dB, other band isolation 60 dB then.

The filter has got two cross - couplings. Capacitive cross - coupling comprised of metal probe generates TZ (transmission zero) on the left side of the passband, inductive coupling comprised of iris generates TZ on the right side of the passband. Corresponding coupling coefficients of the filter and Q_{ext} obtained by synthesis are summarized in following table [3], [4].

coupling	coupling coefficient
1-2	0.04582
2-3	0.03057
3-4	0.02863
4-5	0.02884
5-6	0.03081
6-7	0.04582
2-4	-0.01196
4-6	0.01223
Q_{ext}	18.29

Tab. 1. Coupling coefficients of the designed filter.

The complete fine model of the filter in MWS is shown in Fig. 9. Tuning elements in the fine model are the height of posts (direct couplings) between individual cavities, the disc diameter of capacitive probe (capacitive cross-coupling), the height of iris (inductive cross-coupling), lengths of resonant screws and the height of the tap at input/output resonator. In the coarse model (Fig. 10), capacitors C_1, C_2, C_3, C_4, C_5, C_6 and C_7 represent resonant tuning elements at each resonator, capacitors C_{v12}, C_{v23}, C_{v34}, C_{v45}, C_{v56}, and C_{v67} tuning components for direct couplings, and C_{v24}, C_{v46} tuning elements for cross couplings respectively. Finally, capacitors C_{ex1}, C_{ex2} are used to tune external couplings. The initial response of the designed filter is shown in Fig. 11.

From a convergence point of view it is favorable to pre-tune the coarse model of the filter manually with the help of Tune tool in DS to get the response as close to the design goals as possible. Afterwards, the coarse model was optimized with the help of global optimization method PSO with a combination of local Nelder – Mead Simplex method. Tab. 2 shows the fine model tuning parameters dimensions in each of the TSM iterations. There was a need to set the height of iris to zero value and then tune the coupling via tuning screw L_s in inductive cross-coupling. As can be seen from Fig. 12, a very good agreement between the optimized and measured results has been achieved. The produced filter is shown in Fig. 13.

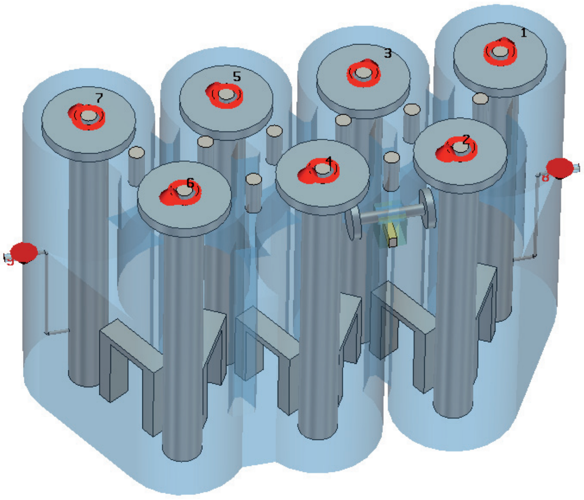


Fig. 9. The fine model of the filter.

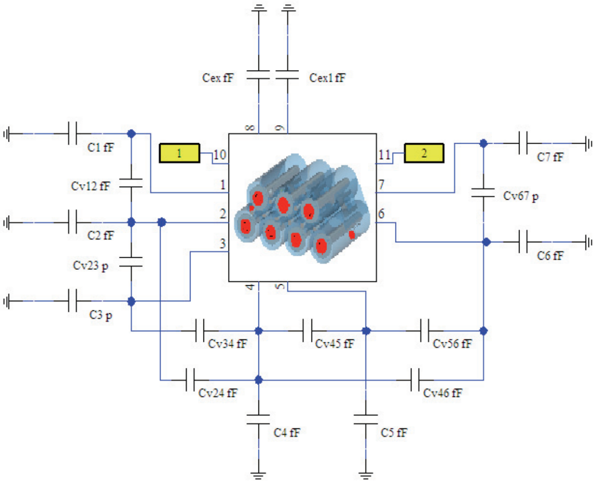


Fig. 10. The coarse model of the filter.

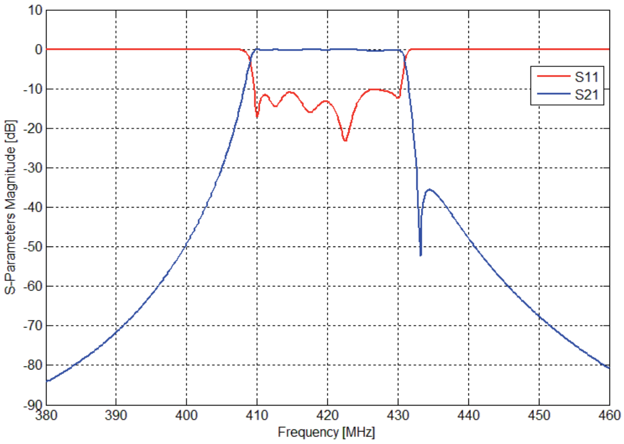


Fig. 11. The initial response of the design.

Coupling	Fine model parameters	Iteration					
		0	1	2	3	4	5
1-2	H_{tram12} [mm]	23.20	28.43	27.17	27.82	27.6	27.59
2-3	H_{tram23} [mm]	21.50	21.81	21.42	21.49	21.51	21.54
3-4	H_{tram34} [mm]	20.0	20.54	20.15	20.21	20.19	20.30
4-5	H_{tram45} [mm]	20.10	25.48	25.79	26.52	26.58	26.74
5-6	H_{tram56} [mm]	21.80	26.7	27.72	28.41	28.55	28.57
6-7	H_{tram67} [mm]	23.20	27.41	27.99	28.12	28.45	28.36
2-4	D_{terc} [mm]	10.0	16.28	17.12	17.02	17.07	17.1
4-6	H_{Dprep} [mm]	62.0	20.02	4.45	1.55	0*	-
	L_S [mm]	-	-	-	-	10	9.19
IN	H_{odb1} [mm]	16.50	19.09	19.61	19.71	19.66	19.64
OUT	H_{odb2} [mm]	16.50	18.67	19.31	19.4	19.53	19.54

Tab. 2. Dimensions of the fine model parameters during optimization.

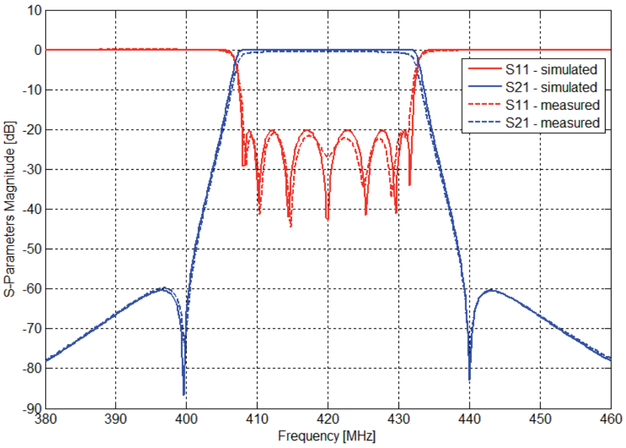


Fig. 12. Optimized and simulated filter response (solid line), measured filter response (dashed line).

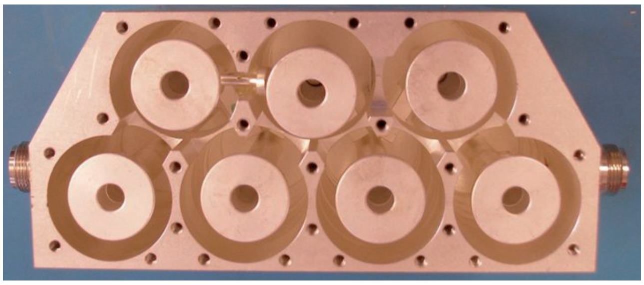


Fig. 13. The produced filter.

6. Conclusion

According to Tab. 2, five TSM iterations were needed in order to reach the optimal filter response. In each of the TSM iterations it was critical to use four hundred cycles of typical optimization methods (Nelder – Mead Simplex method or PSO). The coarse model was simulated approximately two thousand times. The simulation of the coarse model filter took three seconds in average. On the other hand, simulation of the fine model took four hours in average. This means if the fine model filter was optimized in MWS the estimated optimization would take approximately one year. The efficiency of TSM is obvious.

The implemented TSM enables optimization of the complete 3D fine model without any manual determination of calibration constants. With help of macros, calibration constants are automatically determined for each TSM iteration and physical proportions of variables in the fine model are updated accordingly. Efficiency and robustness of the TSM has been verified on the seven-order filter design. The measured results of the manufactured prototype are in a perfect agreement with the simulated ones.

The proposed TSM significantly reduces lead time of filters optimization and simultaneously prevents extensive tuning and costly mechanical modifications on laboratory samples designed by the standard approach.

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