A Novel Design Approach for Microwave Planar Filters

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Abstract— **This paper presents an efficient design approach for large planar filter circuits using very accurate full-electromagnetic simulations. This new hybrid optimisation technique combines the accurate—but expensive— full electromagnetic simulation with the inexpensive—but less accurate—cascaded circuit analysis. By altering the coupling matrix of the cascaded circuit simulation we attain the computational speed of the cascaded simulation, but the accuracy of the full-electromagnetic simulation. To reduce computational costs further, we introduce the multi-dimensional Cauchy method to the cascaded circuit simulation. The proposed techniques result in a considerable gain in design reliability and a significant reduction of computational cost when compared to conventional methods. The new method is demonstrated by the optimisation of a superconductive planar narrow-band 6-Pole filter for space applications. Using our optimisation scheme the co mputational costs can be cut to about 1.5% compared to a full-EM based optimisation.**

I. Introduction

As of now direct optimisation of large filter structures using full EM-simulation techniques is not practical, since direct optimisation of large circuits is computationally very expensive. Optimisation using segmented or cascaded filter structures, as often used today, is less expensive, but introduce usually not neglegtible inaccuracies.

If we require both, the high accuracy of the full EM model and the speed of the simplified model, we suggest to combine the advantages of the two models. We call this a hybrid optimisation technique.

II. Hybrid Optimisation

Any hybrid optimisation relies on two simulation models: a fine model and a coarse model. The fine model is accurate but computationally expensive, whereas the coarse model is fast but less accurate.

In a hybrid optimisation scheme the coarse model is used inside the optimisation loop for fast computations and the fine model is used for verification and, more importantly, to find adequate correction terms for the coarse model.

Hybrid techniques generally work in two phases: a training phase and an application phase. During the training phase, we collect data about the coarse and the fine model for one or a few specific circuit geometries. Based on this data, we derive an algorithm which adjusts the coarse model to make it more accurate. Our goal in the training phase is to derive an adjusted coarse model which mimics the fine model very closely.

In the application phase, we use this corrected coarse model to inexpensively compute new, unknown circuit geometries. The training step might be repeated after several optimisation iterations if necessary.

One well known technique of this approach is space mapping. The systematic application of this method was first suggested by BANDLER [4], [5]. Applying space mapping yields often excellent results for many optimisation problems. Other methods use neural networks as coarse models, which are trained by a few fine model simulations. Details can be found in [6], [7]. Another approach, particularly geared to filter optimisation, is developed in [8] . In this paper YE and MANSOUR propose the introduction of additional lumped element networks, representing stray couplings neglected in the coarse model. These networks are then used to correct the coarse model.

These methods, however, have some limitations. The control of the coarse model response is restricted to manipulations which can be controlled by the model input parameters. Certain electromagnetic phenomenas (like stray couplings) detected in the fine model only—and thus not accessible in the coarse model—cannot be easily integrated in the above mentioned coarse models. This problem often occours in planar high-Q resonator filters. We suggest for this type of optimisation problem the hybrid optimisation by coupling matrix alteration.

III. Hybrid Optimisation by Coupling Matrix Alteration

Our proposed technique of coupling matrix alteration builds on the coupling matrix representation of a filter. This representation describes a resonant-coupled filter completely including all cross-couplings as well as input and output couplings. The theory of direct coupled resonant structures is developed in detail in [2] and [3].

Our method breaks down into a training and an application phase. During training we derive two coupling matrices of the filter: one from the response found by full-EM simulation (fine model), and one from the response found by a cascaded simulation(coarse model). Then we compare the two coupling matrices and apply this knowledge to eliminate inaccuracies in the cascaded circuit model.

The utilization of the coupling information for filter optimisation is recently suggested in [9]. Our algorithm takes this approach further. Rather than adjusting the objective coupling matrix of the optimisation loop, we introduce a new corrected coarse model, which yields almost the accuracy of the fine model. Further, we implement the multi-dimensional Cauchy method as discussed later.

Our goal is the correction of the coarse model's coupling matrix to represent the more accurately the exact fine model coupling matrix. The coarse model's coupling matrix is hence altered by a correction matrix.

To compute the correction matrix we calculate the S-paramter response for an arbitrary filter layout with the geometry parameter vector $\vec{p}$ using both models. Let us define the S-parameter response of the cascaded simulation (coarse model) as $S_c(\vec{p})$ and the response of the Full-EM analysis (fine model) as $S_f(\vec{p})$.

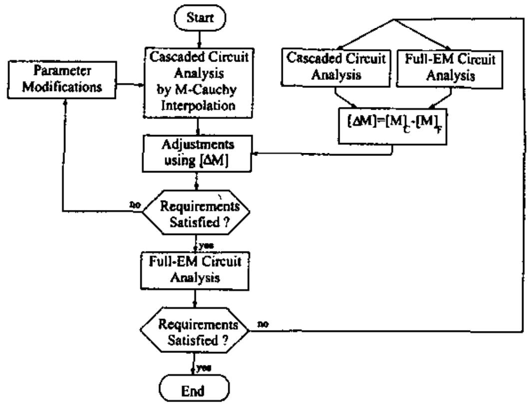

Fig. 1. Optimisation Including Correction of Cascaded Response

From the responses we can derive the respective coupling matrices $[M]_c(\vec{p})$ and $[M]_f(\vec{p})$ using parameter extraction methods. The difference matrix between the two matrices is then defined as

$$[\Delta M](\vec{p}) = [M]_f(\vec{p}) - [M]_c(\vec{p}) \qquad (1)$$

The matrix $[\Delta M](\vec{p})$ contains all additional couplings not included in the cascaded analysis plus corrections of all other couplings. We can use $[\Delta M](\vec{p})$ to adjust the coarse model response at any parameter vector $\vec{p}_x$ such that the adjusted coupling matrix

$$[M]_c^*(\vec{p}_x) = [M]_c(\vec{p}_x) + [\Delta M](\vec{p}) \qquad (2)$$

models the real (full-EM) circuit much closer. Our coarse model includes now stray couplings which are usually not grasped by the coarse model.

Experiments have shown that these additional couplings are almost constant for small changes of the layout geometry. Hence, the same $[\Delta M](\vec{p})$ can be used to correct the coarse model response for any layout containing small geometrical changes. In the example below, we will see that $[\Delta M]$ is quite robust with respect to $\vec{p}$.

Similar to the other hybrid methods, our method requires a training phase to acquire $[\Delta M]$. The subsequent application phase employs the difference matrix for correction of the coarse model.

During application we calculate the circuit's response using the fast coarse model. From the response the coupling matrix is determined and the correction term $[\Delta M]$ is added. From the altered matrix $[M]_c^*$we calculate a new S-parameter response. This response is more accurate, since it includes stray coupling not considered in the coarse model but taken into account by the fine model.

The proposed algorithm for fast and accurate filter circuit analysis can be incorporated into a hybrid optimisation scheme. Rather than calculating the accurate response in the loop using direct EM simulation (the fine model), we derive the response from the adjusted coarse model. This techniques offers a high accuracy in the optimisation without the costs associated with direct EM simulation.

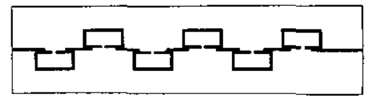

Fig. 2. Layout of Six-pole Filter

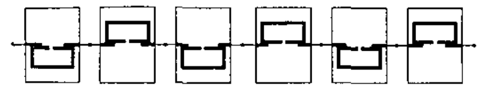

Fig. 3. Cascaded Six-pole Filter

For even more efficiency of the coarse model simulation, we derive the responses of the sub-circuits of the cascaded circuit using the multi-dimensional Cauchy method presented in [1]. This method avoids field simulations completely by implementing a look-up table in conjunction with a multi-dimensional rational-function interpolation algorithm. In doing so, we take *all* expensive calculations out of the optimisation loop. The circuit analysis within the optimisation becomes just a matter of database requests and minimal algebraic computations. The flow of the proposed optimisation scheme is outlined in Figure 1.

Note, that at the end of the optimisation process the performance of the optimised structure is checked by another single Full-EM simulation. If the performance passes the specification the synthesis is complete. If the check fails, the correction $[\Delta M]$ is not valid for the new layout, i.e. $[\Delta M]$ is a function of $\vec{p}$. In that case, a new correction $[\Delta M]$ is calculated using the already known responses of the full EM and cascaded simulations. The optimisation process is repeated using the new $[\Delta M]$.

IV. Demonstration on 6-Pole C-Band Filter Design

Our novel optimisation technique is demonstrated on the design of a 6-pole narrow-band filter. The filter is realised as a planar superconducting thin-film TBCCO microstrip circuit on a $LaAlO_3$-substrate.

The initial filter layout is shown in Figure 2. We employ a the moment-method solver Sonnet *em* as the fine model. A cascaded circuit analysis as shown in Figure 3 is used for the coarse model. We model each sub-section of the circuit using the multi-dimensional Cauchy method. The required database of 225 circuit geometries is built from Sonnet em simulation. This database generation takes 2.4 hours.

First, we optimise the filter using the coarse model only. We use 9 optimisation parameters in total, namely the input and output couling of each resonator plus the resonator length. Since the filter is symmetric we have to optimise three resonators, only. The result of the optimisation is shown in Figure 4 as the solid line.

The optimised filter cannot be exactly verified by a full EM-simulation due to limitation in the underlying moment method solver. The circuit must fall on a discrete mesh, which does not coincide with the optimal layout. Hence, we snap the layout to the nearest mesh points and perform a full EM simulation and a cascaded circuit simulation on the snapped layout.

The two responses from the two simulation methods yield the correction matrix $[\Delta M]$. Using this $[\Delta M]$ we can compute

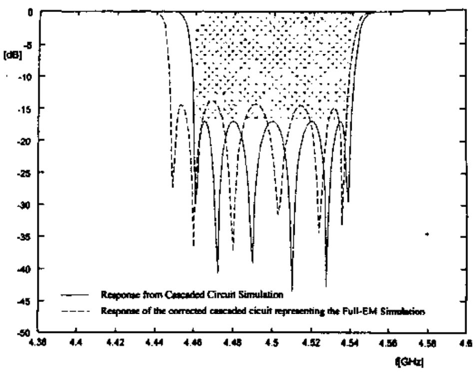

Fig. 4. Response the by Coarse Model Optimised Filter using fine Model simulation and a Coarse Model Simulation. Marked in Gray is the Forbidden Area of the Specifications.

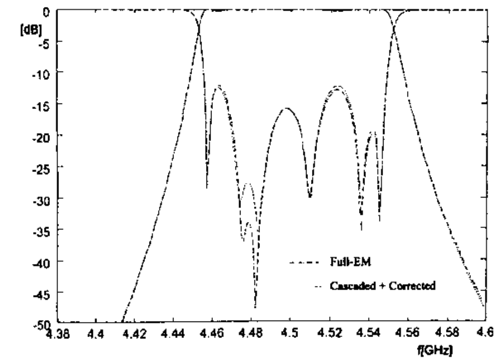

Fig. 6. Response the cascaded filter circuit including the Coupling Matrix correction in comparison with a full-EM simulation

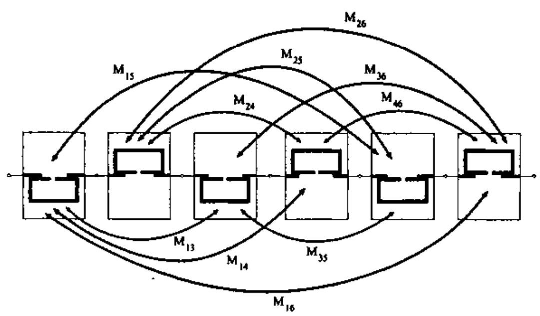

Fig. 5. Additional Couplings in Full-EM Simulation

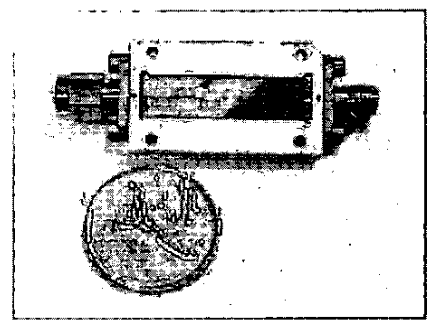

Fig. 7. Photograph of the Six-Pole Filter

the adjusted coarse model response as described above. The response of the cascaded circuit plus the correcting coupling, representing the exact solution, is also shown in Figure 4 as a dotted line.

The responses for the fine model and coarse model analysis are different because the fine model analysis includes additional couplings. The additional couplings are shown in Figure 5.

The optimisation is repeated on the cascaded response including the correction algorithm using $[\Delta M]$ as described above. The optimisation requires 25 iterations and includes one recomputation of the correction matrix by one more full electromagnetic simulation.

After the optimisation is finished, we still have to verify that the response calculated by the corrected coarse model is accurate. Since we have to snap to the mesh again for this verification, we cannot compare the exact layout. Rather a mesh-snapped layout is used again. The comparison of the layout snapped to the closed mesh-node is shown in Figure 6.

It turns out that the optimised corrected response, is almost identical to the response found by full-EM simulation. The graph shows an excellent agreement of the corrected coarse model's response with the full EM model's response. Hence our optimised circuit (layout slightly off the mesh) must be valid.

V. Hardware Verification

Figure shows 7 a six-pole superconduvtive filter designed to verify the approach presented in this paper.

The results of the measurements are shown in Figure 8. The measured response is in excellent agreement with the response, obtained by our corrected coarse model simulation. The response shown is achieved with absolutely no tuning of the hardware. This indicates, that we almost completely eliminated errors from the numerical simulation and optimisation when applying our new developed techniques.

VI. Comparison of Computational Costs

This section gives an overview on the computation times required using different optimisation approaches. The benchmarks are performed on an HP-UX 733 workstation. All times given are CPU-times.

A complete electromagnetic simulation (frequency sweep) of the layout of Figure 2 requires 22,080 CPU-seconds (6 h, 8 min). The simulation of a single resonator, on the other hand, requires only 70 s for a complete frequency sweeps.

The database for the sub-circuit response using Cauchy-method includes five values for each parameter dimension. Hence for building the database, we require 5^3 simulations of the resonator layouts. This determines the database generation time to be 8750 s (2.4 h). A simulation of the complete cascaded circuit using the database and Cauchy method takes then 3 s.

The time required for the complete standard gradient optimi-

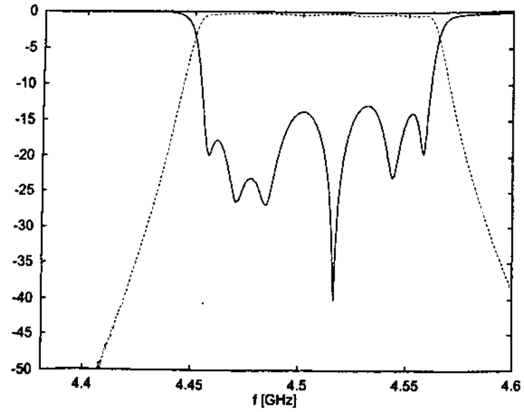

Fig. 8. Measured Frequency Response of Six-Pole Filter Without Tuning

sation process can be summarised in the following formula,

$$t = t_{single} \cdot (1 + n_{par}) \cdot n_{freq} \cdot n_{ite} \quad (3)$$

where t_{single} is the simulation time for a single circuit at a single point, n_{par} is the number of parameters, n_{freq} is the number of frequency samples required, and n_{ite} is the number of iterations necessary to find an optimal solution. In this formula, n_{ite} is the only variable undetermined prior to the optimisation. Experience shows that an optimum result can be achieved with 10 to 20 iterations for problems with around 5 to 10 variables.

When using the full-EM simulation for analysis the optimisation would last for 920 h or 39 days. The exact time could not be determined for obvious reasons. The response of the optimised circuit would be close to the desired response but limited by the discrete grid-snap.

Using the cascaded circuit and rough grid meshing for analysis, the optimisation takes 31500 s or 8.75 h. However, the result is not satisfying. Firstly, the calculations are based on a very rough grid and, secondly, errors introduced by decomposition are present. The accuracy can be enhanced by finer meshing, however, the time penalty is severe.

Implementing the Cauchy method, the total optimisation time is reduced to 2.5 h. This includes the time required for generating the database. The final optimised response is closer to the desired response because we interpolate off-the-grid points. The simulation, however, still suffers from inaccuracies introduced by the decomposition.

When applying our hybrid optimisation scheme, as suggested, the optimisation time is 15 h 16 min. The time includes database generation, two complete EM simulations and 25 optimisation iterations. The error of the method is very small as seen from the comparison of Figure 6.

The benchmark results are summarised as follows

	CPU Time	Error
Conv. Full-EM Optimisation	920 h = 39 days	def. as exact
Conv. Casc. Optimisation	8 h 45 min	very large
Casc. Opti. using Cauchy	2 h 33 min	large
Our Hybrid Optimisation	15 h 16 min	very small

VII. Conclusion

Our Hybrid optimisation scheme combines the advantages of coarse and fine modelling in the analysis. On the one hand, we exploit the coarse model's computational speed in the optimisation loop for a rapid calculation of the optimal circuit layout. On the other hand, we exploit the fine model's accuracy for verifying and adjusting the coarse model.

We showed that for filter optimisation, a correction scheme based on the coupling matrix representation is beneficial. The coupling matrix representation allows us to include stray coupling into the coarse model otherwise neglected.

Our novel approach proposes to correct the coarse model simulation by a difference coupling matrix containing these stray couplings. This difference matrix, derived from a comparison of fine and coarse model simulations, represents all couplings not included by the coarse model, but modelled by the fine model.

Our corrected coarse model, which is used in the optimisation loop, has the computational costs of the coarse model and almost the accuracy of the fine model. To reduce computational costs further we utilized the multi-dimensional Cauchy method for the calculation of the coarse model. The result is a very fast optimisation scheme which yields very accurate results.

The new approach was demonstrated on the design of a planar high-temperature superconductive six-pole filter. With only two complete EM simulations, the filter could be very accurately simulated and optimised. When compared with conventional approaches, our technique is the only one providing a very accurate solution within reasonable computational expenses.

VIII. Acknowledgements

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