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ADAPTIVELY ADJUSTED DESIGN SPECIFICATIONS FOR EFFICIENT OPTIMIZATION OF MICROWAVE STRUCTURES

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Abstract—Novel and computationally efficient method for optimization of microwave structures is presented. The technique is based on the adjustments of the design specifications and exploits the coarse model — computationally cheap representation of the structure being optimized, e.g., equivalent circuit. It is demonstrated that the proposed approach allows rapid design improvement while being simple to implement. Limitations and modifications of the technique are also discussed.

1. INTRODUCTION

Simulation-driven design optimization of microwave structures faces substantial difficulties. Increasing complexity of microwave devices and the demand for high accuracy make the direct optimization involving numerous electromagnetic (EM) simulations impractical because of the computational cost of such a process. Co-simulation [1–3] is only a partial solution because the circuit models with embedded EM components are still directly optimized. On the other hand, EM-based design is the only option for various classes of microwave structures for which no systematic design procedures are available. This applies, in particular, to structures such as ultrawideband (UWB) antennas [4] and substrate integrated circuits [5].

Efficient optimization of microwave structures can be realized using surrogate-based optimization (SBO) principle [6], where the

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optimization burden is shifted to a surrogate model, computationally cheap representation of the structure being optimized (fine model). The successful SBO approaches used in microwave area are space mapping (SM) [7–15] and various forms of tuning [16–19] as well as combinations of both [20–23]. Space mapping builds the surrogate using a physically-based coarse model, typically an equivalent circuit. The coarse model addresses the same physical phenomena as the fine model but in a simplified way (e.g., lumped element circuit equivalent versus full-wave electromagnetic model). This facilitates alignment between the fine model and the surrogate as well as gives good prediction capability of the latter even is a modest amount of fine model data is used to set up the surrogate. Tuning approaches are based on embedding circuit-theory-based tuning elements into the structure of interest using properly located internal ports [18]. Both approaches can be very efficient and yield satisfactory designs after a few full-wave EM simulations of the structures under consideration [7, 8]. Unfortunately, implementation of these methodologies may not be straightforward. In particular, modification of the structure being optimized and engineering experience may be required (tuning), additional mapping and more or less complicated interaction between various auxiliary models is necessary (SM). Also, SM performance heavily depends on the selection of the space mapping transformations used to construct the surrogate.

In this paper, a novel technique is presented that exploits a computationally cheap coarse model, e.g., an equivalent circuit or a coarse-discretization EM model, and the adaptive adjustment of the design specifications. Original design specifications are modified to take into account the difference between the fine and coarse model responses at the current design. The coarse model is then optimized with respect to the modified specifications to produce a new design that — assuming sufficient quality of the coarse model — gives a good prediction of the optimal fine model design with respect to the original specifications. The new method is extremely simple to implement, and, as demonstrated using several examples of microstrip filters, is able to yield a satisfactory design after a few electromagnetic simulations of the structure under considerations.

2. OPTIMIZATION THROUGH DESIGN SPECIFICATIONS ADAPTATION

In this section, we introduce the proposed design optimization methodology as well as discuss its relations with other techniques, particularly space mapping.

2.1. Formulation of the Design Optimization Problem

Let $\mathbf{R}_f$ and $\mathbf{R}_c$ denote the response vectors of a fine and coarse models of the microwave structure of interest. $\mathbf{R}_f$ is evaluated using CPU-intensive EM simulator, $\mathbf{R}_c$ is typically an equivalent circuit, a model described using analytical formulas, or even a coarse-discretization EM model evaluated with the same solver as that used for the fine model. The response vector components are performance parameters, e.g., $|S_{21}|$, evaluated over certain frequency range.

We want to optimize the fine model with respect to a given set of design specifications. Fig. 1(a) shows fine and coarse model response at the optimal design of $\mathbf{R}_c$, corresponding to the bandstop filter example considered in Section 3; design specifications are indicated using horizontal lines.

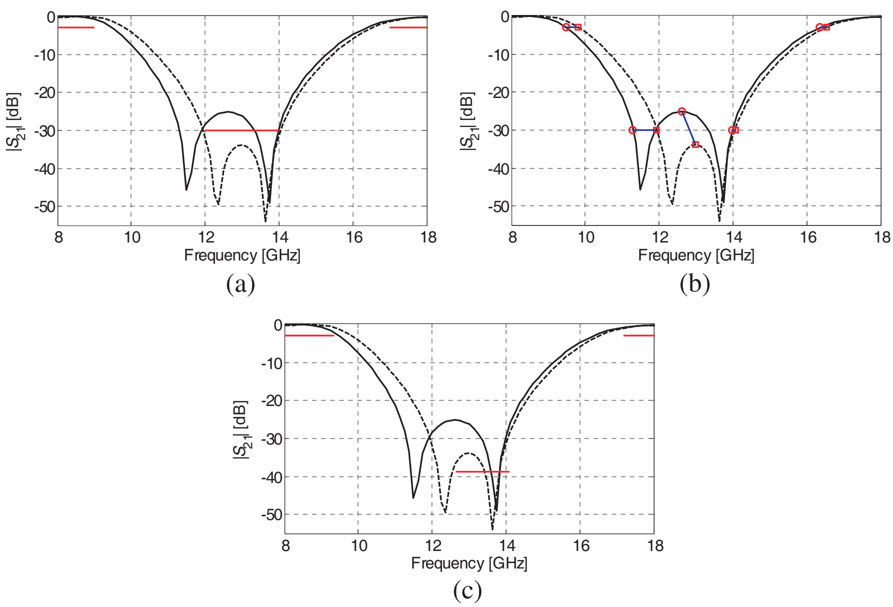

Figure 1. Bandstop filter example (responses of $\mathbf{R}_f$ and $\mathbf{R}_c$ are marked with solid and dashed line, respectively): (a) fine and coarse model responses at the initial design (optimum of $\mathbf{R}_c$) as well as the original design specifications, (b) characteristic points of the responses corresponding to the specification levels (here, -3 dB and -30 dB) and to the local response maxima, (c) fine and coarse model responses at the initial design and the modified design specifications.

2.2. Adaptive Adjustment of the Design Specifications: Optimization Procedure

The proposed optimization procedure consists of the following two simple steps that can be iterated if necessary:

1. Modify the original design specifications in order to take into account the difference between the responses of $\mathbf{R}_f$ and $\mathbf{R}_c$ at their characteristic points.
2. Obtain a new design by optimizing the coarse model with respect to the modified specifications.

Characteristic points of the responses should correspond to the design specification levels. They should also include local maxima/minima of the respective responses at which the specifications may not be satisfied. Fig. 1(b) shows characteristic points of $\mathbf{R}_f$ and $\mathbf{R}_c$ for our bandstop filter example. The points correspond to -3 dB and -30 dB levels as well to the local maxima of the responses. As one can observe in Fig. 1(b) the selection of points is rather straightforward.

In the first step of the proposed optimization procedure, the design specifications are modified (or mapped) so that the level of satisfying/violating the modified specifications by the coarse model response corresponds to the satisfaction/violation levels of the original specifications by the fine model response.

More specifically, for each edge of the specification line, the edge frequency is shifted by the difference of the frequencies of the corresponding characteristic points, e.g., the left edge of the specification line of -30 dB is moved to the right by about 0.7 GHz, which is equal to the length of the line connecting the corresponding characteristic points in Fig. 1(b). Similarly, the specification levels are shifted by the difference between the local maxima/minima values for the respective points, e.g., the -30 dB level is shifted down by about 8.5 dB because of the difference of the local maxima of the corresponding characteristic points of $\mathbf{R}_f$ and $\mathbf{R}_c$. Modified design specifications are shown in Fig. 1(c).

The coarse model is subsequently optimized with respect to the modified specifications and the new design obtained this way is treated as an approximated solution to the original design problem (i.e., optimization of the fine model with respect to the original specifications). Steps 1 and 2 can be repeated if necessary. As demonstrated in Section 3, substantial design improvement is typically observed after the first iteration, however, additional iterations may bring further enhancement.

2.3. Some Remarks on Coarse Models

It is assumed that the coarse model is physics-based, in particular, the adjustment of the design variables has similar effect on the response for both $\mathbf{R}_f$ and $\mathbf{R}_c$. In such a case the coarse model design that is obtained in the second stage of the proposed procedure (i.e., optimal with respect to the modified specifications) will be (almost) optimal for $\mathbf{R}_f$ with respect to the original specifications. As shown in Fig. 1, the absolute matching between the models is not as important as the shape similarity.

If the coarse model is lacking the aforementioned similarity, the proposed method may not work. However, in some cases, a generalized approach described in Section 4 can be used.

In order to reduce the overhead related to coarse model optimization (step 2 of the proposed procedure) the coarse model should be computationally as cheap as possible. For that reason, equivalent circuits or models based on analytical formulas are preferred. Unfortunately, such models may not be available for many structures including antennas, certain types of waveguide filters and substrate integrated circuits. In all such cases, it is possible to implement the coarse model using the same EM solver as the one used for the fine model but with coarser discretization. To some extent, this is the easiest and the most generic way of creating the coarse model. Also, it allows a convenient adjustment of the trade-off between the quality of $\mathbf{R}_c$ (i.e., the accuracy in representing the fine model) and its computational cost. For popular EM solvers (e.g., CST Microwave Studio [24], Sonnet **em** [25], FEKO [26]) it is possible to make the coarse model 20 to 100 faster than the fine model while maintaining accuracy that is sufficient for the method presented here.

2.4. Relations with Other Methods

When compared to space mapping and tuning, the two design optimization methodologies mentioned in the introduction, the technique presented here appears to be much simpler to implement. Unlike space mapping, it does not use any extractable parameters (which are normally found by solving a separate nonlinear minimization problem), the problem of the surrogate model selection [27, 28] (i.e., the choice of the transformation and its parameters) does not exist, and the interaction between the models is very simple (only through the design specifications). Unlike tuning methodologies, our method does not require any modification of the optimized structure (such as "cutting" and insertion of the tuning components [21]).

The lack of extractable parameters is an additional advantage of the method proposed here when compared to some other approached (e.g., space mapping). The computational overhead related to parameter extraction, while negligible for very fast coarse model (e.g., equivalent circuit), may substantially increase the overall design cost if the coarse model is relatively expensive (e.g., implemented through coarse-discretization EM simulation). Thus, our technique offers — for such cases — a reduction of the overall design optimization cost.

It should be emphasized that the presented method is different from frequency space mapping [7] as the latter only allows linear frequency scaling of the form $\omega \leftarrow \alpha_0 + \alpha_1 \cdot \omega$. The method proposed here: (i) allows us to take into account nonlinear frequency dependence between the model responses, as well as vertical shifts, e.g., as shown in Fig. 1, (ii) does not use any extractable parameters (parameters of the frequency SM are obtained by solving a nonlinear regression sub-problem) and it is, therefore, simpler to implement and computationally cheaper. Section 3 provides numerical comparison between frequency SM and the approach presented in this work that indicates better performance and wider range of applicability of the latter.

3. VERIFICATION EXAMPLES

In this section, we demonstrate the efficiency of the proposed methodology through the design of several microstrip filters. In each case, the optimized design is obtained after just one or two full-wave EM simulations of the respective structure.

In order to assess the quality of the design, the notion of "specification error" is used throughout this section, which is defined as a minimax error, i.e., the maximum violation (in dB) of the design specifications in the frequency band of interest.

3.1. Double Folded Stub Bandstop Filter [29]

Consider a double folded stub (DFS) bandstop filter [29] (Fig. 2). The design parameters are $\mathbf{x} = [L_1\ L_2\ S]^T$ mil; W is set to 5 mils. $\mathbf{R}_f$ is simulated in Sonnet **em** [25]. $\mathbf{R}_c$, Fig. 7, is implemented in Agilent ADS [30]. The design specifications are $|S_{21}| \leq -30$ dB for 12 GHz $\leq \omega \leq$ 14 GHz, and $|S_{21}| \geq -3$ dB for 6 GHz $\leq \omega \leq$ 9 GHz and 17 GHz $\leq \omega \leq$ 20 GHz. The initial design is $\mathbf{x}^{(0)} = [81\ 88\ 6.2]^T$ mil (the optimal solution of $\mathbf{R}_c$, specification error +4.8 dB).

The filter was optimized using the procedure of Section 2. In fact, only one iteration of this procedure was performed which yielded a very good design $\mathbf{x}^{(0)} = [86\ 82\ 8.9]^T$ mil (specification error −1.6 dB).

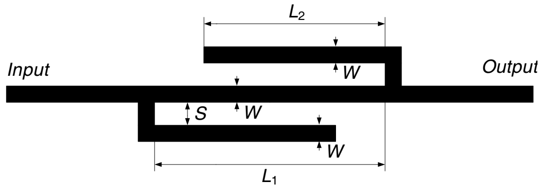

Figure 2. DFS filter: geometry [29].

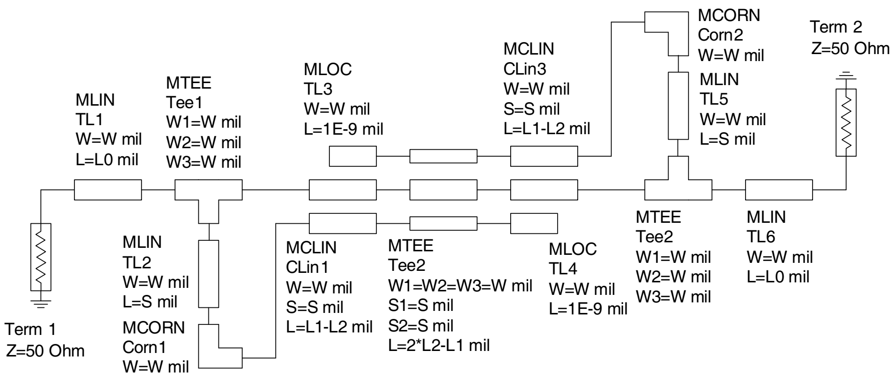

Figure 3. DFS filter: coarse model (Agilent ADS).

Fig. 3 shows the fine and coarse model response at the optimal solution of $\mathbf{R}_c$, optimized with respect to the modified specifications shown in Fig. 1(c).

For the sake of comparison, the DFS filter was also optimized using frequency SM [8] of the form discussed in Section 2.4. Frequency SM was able to shift the fine model response slightly to the right on the frequency scale (with respect to the initial design) and then got stuck at $[86.5\ 87.5\ 5.0]^T$ mm (specification error +5.1 dB, which is worse than at $\mathbf{x}^{(0)}$). The reason is that frequency SM is not able to account for the "vertical" misalignment between the coarse and fine model responses.

In practice, frequency SM is often use as an auxiliary mapping in combination with input, output and/or implicit SM [8]. Here, we use it as a stand-alone technique in order to emphasize the differences frequency SM and the approach introduced in this work.

3.2. Bandpass Microstrip Filter [31]

As the second example, consider the bandpass microstrip filter with open stub inverter [31] (Fig. 5). The design parameters are $\mathbf{x}$ =

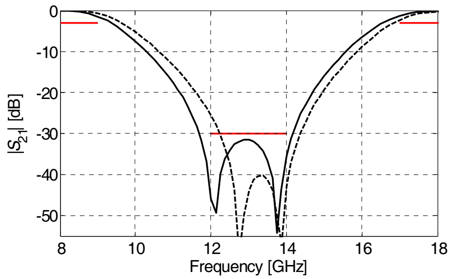

Figure 4. DFS filter: fine (solid line) and coarse (dashed line) model responses at the design obtained after one iteration of the proposed optimization procedure.

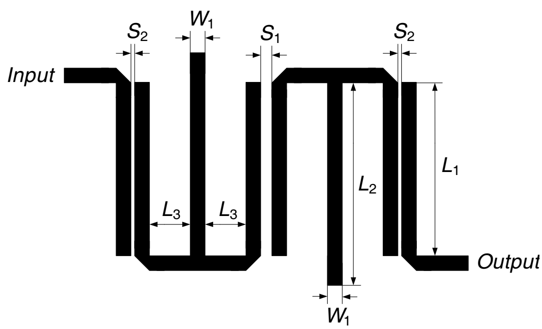

Figure 5. Bandpass filter with open stub inverter: geometry [31].

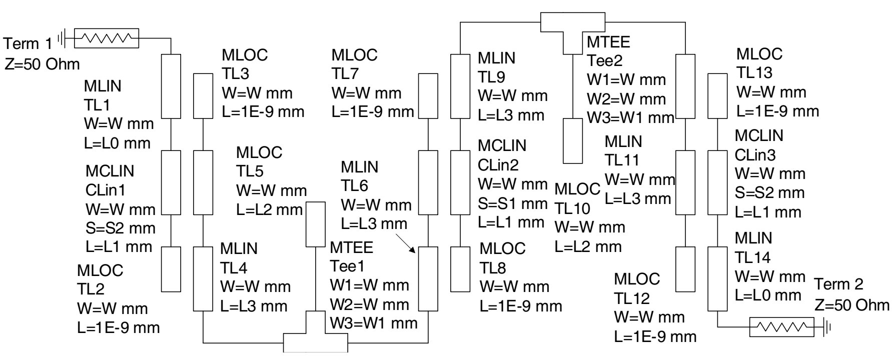

Figure 6. Bandpass filter with open stub inverter: coarse model (Agilent ADS).

$[L_1\ L_2\ L_3\ S_1\ S_2\ W_1]^T$. The fine model is simulated in FEKO [26]. The design specifications are $|S_{21}| \leq -20\,\text{dB}$ for $1.5\,\text{GHz} \leq \omega \leq 1.8\,\text{GHz}$, $|S_{21}| \geq -3\,\text{dB}$ for $1.95\,\text{GHz} \leq \omega \leq 2.05\,\text{GHz}$ and $|S_{21}| \leq -20\,\text{dB}$ for $2.2\,\text{GHz} \leq \omega \leq 2.5\,\text{GHz}$. The coarse model is implemented in Agilent ADS [30] (Fig. 6). The initial design is the coarse model optimal solution $\mathbf{x}^{(0)} = [25.00\ 5.00\ 1.221\ 0.652\ 0.187\ 0.100]^T$ mm (specification error +15.7 dB).

The first iteration of our optimization procedure already yielded a design satisfying the specifications, $\mathbf{x}^{(1)} = [23.79\ 5.00\ 1.00\ 0.694\ 0.192\ 0.10]^T$ mm (specification error −0.6 dB). After the second iteration, the design was further improved to $\mathbf{x}^{(2)} = [23.68\ 5.00\ 1.00\ 0.717\ 0.193\ 0.10]^T$ mm (specification error −1.7 dB). Fig. 7 shows the fine and coarse model responses at $\mathbf{x}^{(0)}$ and the fine model response at the final design.

Again, for the sake of comparison, the filter was also optimized using the frequency SM algorithm. The design obtained in three iterations, $[23.66\ 5.00\ 1.00\ 0.654\ 0.188\ 0.100]^T$ mm, satisfies the design specifications, however, it is not as good at the one obtained using the procedure proposed in this work (specification error −0.8 dB).

3.3. Capacitively-coupled Dual-behavior Resonator Filter [32]

Our third example is a second-order capacitively-coupled dual-behavior resonator (CCDBR) microstrip filter [32] shown in Fig. 8. The design parameters are $\mathbf{x} = [L_1\ L_2\ L_3\ S]^T$. The fine model $\mathbf{R}_f$ is simulated in FEKO [26]. The coarse model $\mathbf{R}_c$ is also the structure of Fig. 8

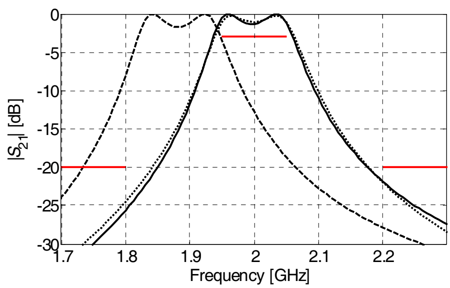

Figure 7. Bandpass filter with open stub inverter: $\mathbf{R}_f$ response (solid line) at the final design obtained after two iterations of our optimization procedure; fine (dashed line) and coarse (dotted line) model responses at the initial design.

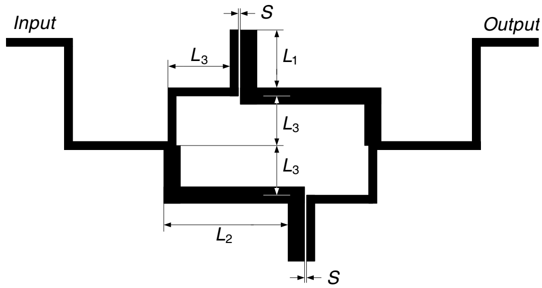

Figure 8. CCDBR filter: geometry [32].

simulated in FEKO, however, using a coarser discretization. The total mesh number is 668 for the fine model (evaluation time about 12 minutes) and 72 for the coarse model (evaluation time 20 seconds). This example illustrates how the coarse-discretization model can be efficiently used in the surrogate-based design optimization even though the evaluation time ratio between the fine and coarse model is only 36.

The design specifications are $|S_{21}| \leq -20\,\text{dB}$ for $2.0\,\text{GHz} \leq \omega \leq 3.4\,\text{GHz}$, $|S_{21}| \geq -3\,\text{dB}$ for $3.8\,\text{GHz} \leq \omega \leq 4.2\,\text{GHz}$, and $|S_{21}| \leq -20\,\text{dB}$ for $4.6\,\text{GHz} \leq \omega \leq 6.0\,\text{GHz}$. The initial design is $\mathbf{x}^{(0)} = [3.0\ 4.0\ 1.0\ 0.1]^T$ mm (specification error +27.5 dB).

The first iteration of the proposed optimization procedure already yields a design satisfying the specifications, $\mathbf{x}^{(1)} = [3.8\ 4.02\ 1.078\ 0.061]^T$ mm (specification error −1.6 dB). After the second iteration, the design was further improved to $\mathbf{x}^{(2)} = [3.8\ 4.13\ 1.011\ 0.058]^T$ mm (specification error −2.1 dB). Fig. 9 shows the fine and coarse model responses at $\mathbf{x}^{(0)}$ and the fine model response at the final design.

For this test problem, the computational overhead related to the evaluation of the coarse model cannot be neglected. The number of coarse model evaluations at the first iteration and the second iteration of the optimization procedure was 92 and 48, respectively. The total cost of evaluating the coarse model corresponds to about 4 evaluations of the fine model. Thus, the total optimization cost is low and corresponds to about 6 fine model evaluations.

The CCDBR filter was also optimized using frequency SM. The design $[3.8\ 3.97\ 1.074\ 0.053]^T$ mm (specification error −1.5 dB) was obtained in three iterations. It is worse than the design obtained with our technique and the computational cost is much higher (equivalent to about 12 fine model evaluations), partially because of the extra overhead related to the parameter extraction process.

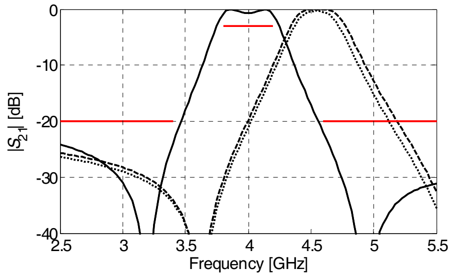

Figure 9. CCDBR filter: fine model response (solid line) at the final design obtained after two iterations of the proposed optimization procedure; fine (dashed line) and coarse (dotted line) model responses at the initial design.

4. GENERALIZED OPTIMIZATION PROCEDURE

In this section, a modified design optimization procedure is presented that can be applied if the similarity between the coarse and fine model responses is not sufficient — in the sense discussed in Section 2 — to apply the basic version of the proposed method. The modification consists of an additional step, which is preconditioning of the coarse model by changing a reference design. This is done using a single space-mapping-like parameter extraction process. The generalized optimization procedure is illustrated using a Chebyshev bandpass filter.

4.1. Coarse Model Preconditioning

If the similarity between the fine and coarse model response is not sufficient the proposed technique may not work well. In many cases, however, using different reference design for the fine and coarse models may help. In particular, $\mathbf{R}_c$ can be optimized with respect to the modified specifications starting not from $\mathbf{x}^{(0)}$ (the optimal solution of $\mathbf{R}_c$ with respect to the original specifications), but from another design, say $\mathbf{x}_c^{(0)}$, at which the response of $\mathbf{R}_c$ is as similar to the response of $\mathbf{R}_f$ at $\mathbf{x}^{(0)}$ as possible. Such a design can be obtained as follows [7]:

$$\mathbf{x}_c^{(0)} = \arg\min_{\mathbf{z}} ||\mathbf{R}_f(\mathbf{x}^{(0)}) - \mathbf{R}_c(\mathbf{z})|| \quad (1)$$

At iteration i of the proposed optimization procedure, the optimal design of the coarse model $\mathbf{R}_c$ with respect to the modified specifications, $\mathbf{x}_c^{(i)}$, has to be translated to the corresponding fine model design, $\mathbf{x}^{(i)}$, as follows $\mathbf{x}^{(i)} = \mathbf{x}_c^{(i)} + (\mathbf{x}^{(0)} - \mathbf{x}_c^{(0)})$. Note that the preconditioning procedure (1) is performed only once for the entire optimization process.

The idea of coarse model preconditioning is borrowed from space mapping (more specifically, from the original space mapping concept [7]). In practice, the coarse model can be "corrected" to reduce its misalignment with the fine model using any available degrees of freedom, for example, preassigned parameters as in implicit space mapping [33].

4.2. Example: Third-order Chebyshev Bandpass Filter [34]

We illustrate the operation of the generalized procedure using the 3rd-order Chebyshev bandpass filter [34] (Fig. 10). The design variables are $\mathbf{x} = [L_1\ \ L_2\ \ S_1\ \ S_2]^T$ mm; $W_1 = W_2 = 0.4$ mm. The fine model is simulated in Sonnet **em** [25]. The design specifications are $|S_{21}| \geq -3$ dB for 1.8 GHz $\leq \omega \leq$ 2.2 GHz, and $|S_{21}| \leq -20$ dB for 1.0 GHz $\leq \omega \leq$ 1.6 GHz and 2.4 GHz $\leq \omega \leq$ 3.0 GHz. The coarse model is implemented in Agilent ADS [30] (Fig. 11).

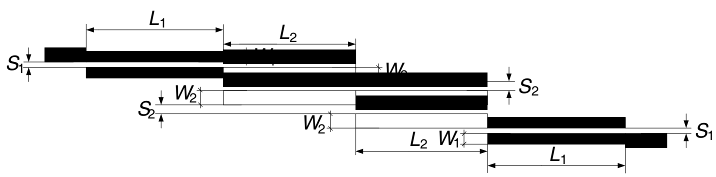

Figure 10. Third-order Chebyshev bandpass filter: geometry [34].

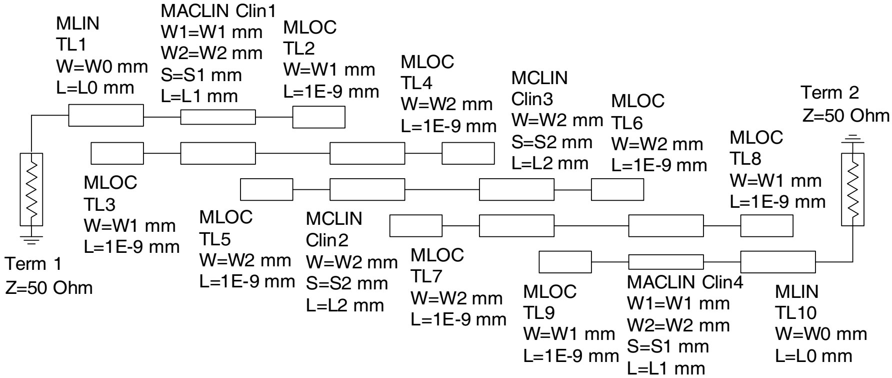

Figure 11. Third-order Chebyshev filter: coarse model (Agilent ADS).

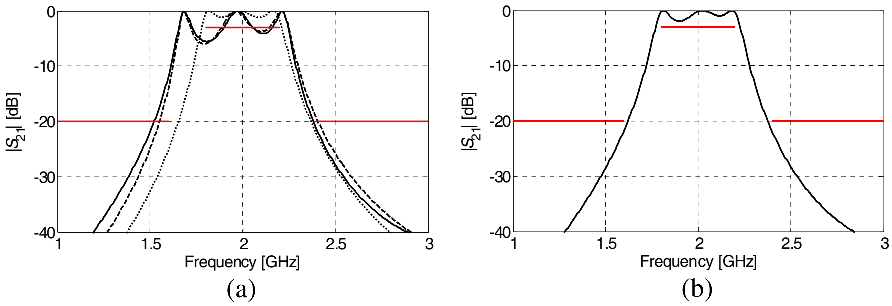

Figure 12. Third-order Chebyshev filter: (a) fine (solid line) and coarse (dotted line) model responses at the initial design $\mathbf{x}^{(0)}$ and the coarse model response (dashed line) design at $\mathbf{x}_c^{(0)}$; (b) fine model response (solid line) at the design obtained after two iterations of our generalized optimization procedure.

Figure 12(a) shows the fine and coarse model response at the initial design $\mathbf{x}^{(0)} = [14.6\ 15.3\ 0.56\ 0.53]^T$ mm. Large ripples in the passband of the fine model response and small ripples of the coarse model response prevent us from directly using the proposed optimization procedure. Using (1), a new design $\mathbf{x}_c^{(0)} = [14.56\ 15.8\ 0.687\ 0.316]^T$ mm was found so that $\mathbf{R}_c(\mathbf{x}_c^{(0)})$ is very similar to $\mathbf{R}_f(\mathbf{x}^{(0)})$ as shown in Fig. 12(b). Using $\mathbf{x}_c^{(0)}$, the generalized optimization procedure was executed yielding $\mathbf{x}^{(1)} = [14.6\ 14.8\ 0.43\ 0.76]^T$ mm (specification error is -0.5 dB) and $\mathbf{x}^{(2)} = [14.6\ 14.8\ 0.42\ 0.82]^T$ mm (specification error -1.1 dB).

5. CONCLUSION

An efficient optimization procedure based on design specifications adjustment is presented. The new technique allows us to yield a satisfactory design after one or two EM simulations and it is very simple to implement. Its robustness is demonstrated through several microwave design optimization examples.

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