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VARIABLE-FIDELITY DESIGN OPTIMIZATION OF MICROWAVE DEVICES USING MULTI-DIMENSIONAL CAUCHY APPROXIMATION AND COARSELY DISCRETIZED ELECTROMAGNETIC MODELS

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Abstract—Application of multi-dimensional Cauchy approximation and coarse-discretization electromagnetic (EM) models to surrogate-based optimization of microwave structures is discussed. Space mapping is used as an optimization engine with the surrogate model constructed as a Cauchy approximation of the coarsely discretized device EM model. The proposed approach allows us to perform computationally efficient optimization of microwave structures without using circuit-equivalent coarse models traditionally exploited by space mapping algorithms. We demonstrate our technique through design of a range of microwave devices, including filters, antennas, and transitions. Comprehensive numerical verification of the proposed methodology is carried out with satisfactory designs obtained — for all considered devices — at a computational cost corresponding to a few full-wave simulations.

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1. INTRODUCTION

Electromagnetic (EM) simulation offers accurate but computationally expensive evaluation of microwave devices and circuits. Therefore, using a high-accuracy full-wave EM simulator to optimize complex structures is usually impractical. One of possible alternatives is circuit decomposition, i.e., breaking down an EM model into smaller parts and combining them in a circuit simulator to reduce the CPU-intensity of the design process [1–3]. This is only a partial solution though because the EM-embedded co-simulation model is still subject to direct optimization. Adjoint sensitivity approaches [4], on the other hand, aim at efficiently estimating the sensitivity information required for gradient-based optimization. They require post processing of stored electromagnetic fields to extract the sensitivity information.

Despite these difficulties, simulation-driven design is the only available option in many practical cases. That includes, in particular, some of emerging classes of structures such as ultrawideband (UWB) antennas [5–9] and substrate-integrated circuits [10]. Due to the lack of good analytical models and systematic design procedures, satisfactory design is typically obtained using tedious and time-consuming parameter sweeps involving numerous full-wave EM simulations.

Practical, i.e., computationally efficient, EM-simulation-driven design can be realized using surrogate-based optimization (SBO) [11, 12]. The most successful SBO approaches in microwave engineering to date are space mapping (SM) [13–27], tuning [28–31], various combinations of SM and tuning [32–35], as well as response correction techniques [36, 37]. Tuning can be extremely efficient, however, it is an invasive technique because it requires modification of the structure being optimized, which is necessary to insert the tuning components [31]. Also, tuning may not be able to directly handle radiating structures. Moreover, applying tuning to certain parameters (e.g., cross-sectional ones, microstrip width, etc.) is not straightforward [33]. Space mapping is a more versatile methodology that allows efficient optimization of expensive (or "fine") EM-based models by means of the iterative optimization and updating of less accurate but cheaper to evaluate "coarse" models. The coarse model is supposed to be a physically-based representation of the fine model so that it has a good prediction capability. On the other hand, the coarse model should be computationally much cheaper than the fine model. Therefore, equivalent-circuit models or models exploiting analytical formulas are preferred [14]. Reliable equivalent-circuit models, however, may be difficult to develop for certain types of microwave devices (e.g., UWB antennas and their feeding networks, low-reflective broadband interconnects, substrate integrated hybrid circuits). Also, an extra simulator of the coarse model must be invoked in the optimization process.

Probably the most generic approach to creating a coarse model is by exploiting the same EM solver as the one used to evaluate the fine model with a coarser discretization. While coarsely discretized EM models can be quite accurate, they are usually computationally too expensive to be directly used in space mapping optimization process. In order to take full advantage of the space mapping principle, the coarse model should evaluate at least two to three orders of magnitude faster than the fine model. Otherwise, the computational overhead related to numerous coarse model evaluations necessary to execute the basic steps of the SM algorithm may degrade space mapping efficiency.

Parameterized Cauchy models [38] offer a good alternative to direct use of the coarsely discretized EM models. This approach utilizes a number of coarse model simulations to model an arbitrary response as a ratio of two polynomials. The coefficients of these polynomials are determined through the solution of a much faster optimization approach. This approach was first developed for one-dimensional responses where typically a frequency domain response is modeled [39]. Later, it was extended to the multi-dimensional case [40]. Previous approaches for multi-dimensional Cauchy models suffered from the possibility of generating a spurious solution [41]. A more robust approach for obtaining the coefficients of the polynomials, which is based on a fast linear programming formulation and excludes any non physical solutions, can be found in [42].

In this work, we propose an efficient approach for creating reliable coarse models for space mapping optimization. We utilize a multi-dimensional Cauchy model [38, 42] of the coarsely discretized device EM model. The coarse model built in this way is very fast and easy to optimize. An additional circuit-based coarse model is not needed and space mapping optimization can be implemented using a single EM simulator. The proposed approach is illustrated and verified through the design optimization of two microstrip filters, a monopole antenna, and a cpw-to-microstrip transition.

2. DESIGN OPTIMIZATION USING SPACE MAPPING

In this section, we formulate the design optimization problem, recall the basics of space mapping optimization, as well as discuss the role and important characteristics of the coarse model — the key component of the SM algorithm.

2.1. Design Optimization Problem

Our goal is to solve the following problem

$$\mathbf{x}_f^* \in \arg\min_{\mathbf{x}\in X_f} U\left(\mathbf{R}_f(\mathbf{x})\right) \tag{1}$$

where $\mathbf{R}_f \in R^m$ denotes the response vector of the fine model of the device of interest, e.g., the modulus of the reflection coefficient $|S_{11}|$ evaluated at m different frequencies. U is a given scalar merit function, e.g., a minimax function with upper and lower specifications. Vector $\mathbf{x}_f^*$ is the optimal design to be determined. The fine model is assumed to be computationally expensive so that its direct optimization is usually prohibitive.

2.2. Space Mapping Optimization Basics

Space mapping (SM) is probably the most successful surrogate-based optimization technique in microwave engineering. Instead of solving the problem (1) directly, SM generates a sequence of approximate solutions to (1), denoted as $\mathbf{x}^{(i)}$, $i = 0, 1, 2, \ldots$, and a family of surrogate models $\mathbf{R}_s^{(i)}$, as follows [14]:

$$\mathbf{x}^{(i+1)} = \arg\min_{\mathbf{x}} U\left(\mathbf{R}_s^{(i)}(\mathbf{x})\right) \tag{2}$$

Here, $\mathbf{x}^{(0)}$ is the initial design. The surrogate model $\mathbf{R}_s^{(i)}$ is a representation of $\mathbf{R}_f$ created using available fine model data, and updated after each iteration.

SM constructs a surrogate model based on the coarse model $\mathbf{R}_c$: a less accurate but computationally cheap representation of the fine model. Let $\bar{\mathbf{R}}_s$ be a generic SM surrogate model, i.e., $\mathbf{R}_c$ composed with suitable (usually linear) transformations. At the ith iteration, the surrogate model $\mathbf{R}_s^{(i)}$ is defined as

$$\mathbf{R}_s^{(i)}(\mathbf{x}) = \bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{p}^{(i)}) \tag{3}$$

where

$$\mathbf{p}^{(i)} = \arg\min_{\mathbf{p}} \sum\nolimits_{k=0}^{i} w_{i.k} ||\mathbf{R}_f(\mathbf{x}^{(k)}) - \bar{\mathbf{R}}_s(\mathbf{x}^{(k)}, \mathbf{p})|| \tag{4}$$

is a vector of model parameters and $w_{i.k}$ are weighting factors; a common choice of $w_{i.k}$ is $w_{i.k} = 1$ for all i and all k (all previous designs contribute to the parameter extraction process) or $w_{i.1} = 1$ and $w_{i.k} = 0$ for $k < i$ (the surrogate model depends on the most recent design only).

Various space mapping surrogate models are available [13, 14]. They can be categorized into four groups:

- Models based on a (usually linear) distortion of coarse model parameter space, e.g., input SM of the form $\bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{p}) = \bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{B}, \mathbf{c}) = \mathbf{R}_c(\mathbf{B} \cdot \mathbf{x} + \mathbf{c})$ [13];
- Models based on a distortion of the coarse model response, e.g., output SM of the form $\bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{p}) = \bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{d}) = \mathbf{R}_c(\mathbf{x}) + \mathbf{d}$ [14];
- Implicit space mapping, where the parameters used to align the surrogate with the fine model are separate from the design variables, i.e., $\bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{p}) = \bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{x}_p) = \mathbf{R}_{c.i}(\mathbf{x}, \mathbf{x}_p)$, with $\mathbf{R}_{c.i}$ being the coarse model dependent on both the design variables $\mathbf{x}$ and so-called preassigned parameters $\mathbf{x}_p$ (e.g., dielectric constant, substrate height) that are normally fixed in the fine model but can be freely altered in the coarse model [43];
- Custom models exploiting characteristic parameters of a given design problem. The most commonly used characteristic parameter is frequency. Frequency SM exploits a surrogate model of the form $\bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{p}) = \bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{F}) = \mathbf{R}_{c.f}(\mathbf{x}, \mathbf{F})$ [13], where $\mathbf{R}_{c.f}$ is a frequency-mapped coarse model. Here, the coarse model is evaluated at frequencies different from the original frequency sweep for the fine model, according to the mapping $\omega \rightarrow f_1 + f_2\omega$, with $\mathbf{F} = [f_1 f_2]^T$.

The basic SM types can be combined, e.g., the surrogate model employing both input, output and frequency SM types would be as follows: $\bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{p}) = \bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{c}, \mathbf{d}, \mathbf{F}) = \mathbf{R}_{c.f}(\mathbf{x} + \mathbf{c}, \mathbf{F}) + \mathbf{d}$. The rationale for this is that a properly chosen mapping may significantly improve the performance of the SM algorithm, however, the optimal selection of the mapping type for a given design problem is not trivial [27, 44, 45].

The space mapping optimization algorithm flow can be described as follows:

1. Set $i = 0$; choose the initial design solution $\mathbf{x}^{(0)}$;
2. Evaluate the fine model to find $\mathbf{R}_f(\mathbf{x}^{(i)})$;
3. Obtain the surrogate model $\mathbf{R}_s^{(i)}$ using (3) and (4);
4. Given $\mathbf{x}^{(i)}$ and $\mathbf{R}_s^{(i)}$, obtain $\mathbf{x}^{(i+1)}$ using (2);
5. If the termination condition is not satisfied go to Step 2; else terminate the algorithm;

Typically, $\mathbf{x}^{(0)} = \arg\min\{\mathbf{x} : U(\mathbf{R}_c(\mathbf{x}))\}$, i.e., it is the optimal solution of the coarse model: the best initial design normally available. We usually terminate the algorithm when it converges (i.e., $||\mathbf{x}^{(i)} - \mathbf{x}^{(i-1)}||$ is smaller than some user-defined value) or when the maximum number of iterations (or, more often, the number of $\mathbf{R}_f$ evaluations) is exceeded.

2.3. Coarse Models and Performance of Space Mapping

It is of primary importance for the performance of SM optimization that the coarse model is physically-based, i.e., it describes the same phenomena as the fine model. This would ensure that the surrogate model constructed using $\mathbf{R}_c$ has a good prediction capability [27]. If the surrogate model is a sufficiently good representation of the fine model, the SM algorithm typically requires a few fine model evaluations to yield a satisfactory solution, substantially less than for any method directly involving the fine model in the optimization loop [13, 14]. On the other hand, $\mathbf{R}_c$ should be computationally much cheaper than $\mathbf{R}_f$ so that the overhead due to numerous coarse model evaluations while optimizing the surrogate model (2) and solving the parameter extraction sub-problem (4) is reasonably small.

The preferred choice for the coarse model is an equivalent circuit implemented in a circuit-based simulator, e.g., Agilent ADS [46]. Unfortunately, for many structures (e.g., antennas, substrate integrated circuits), it is difficult or impossible to build a reliable circuit-based coarse model. On the other hand, the accuracy of such models is often insufficient, which may result in the SM process performing poorly. If the coarse model is insufficiently accurate, the SM algorithm may need more fine model evaluations or may even fail to find a good quality design. Also, it might be difficult to find a suitable combination of SM transformations to construct a sufficiently good surrogate model [27, 44].

3. COARSE MODELS USING COARSELY DISCRETIZED EM MODELS AND MULTI-DIMENSIONAL CAUCHY APPROXIMATIONS

A coarse model that is accurate and yet computationally cheap can be constructed by approximating the response of coarse-discretization EM model data obtained by sampling the design space using a suitable design of experiments technique. In this section, we discuss basic features of coarsely discretized EM models and discuss the method of creating the coarse model using multi-dimensional Cauchy approximation.

3.1. Coarse-mesh EM-simulation-based Models

One of the possible ways of implementing the coarse model is by exploiting the same EM solver used to evaluate the fine model, however, with coarser discretization. In this case, however, it is difficult to find a satisfactory trade-off between the coarse model accuracy and evaluation time. The evaluation time of $\mathbf{R}_c$ should be at least two orders of magnitude smaller than that of $\mathbf{R}_f$ in order to make the overhead of solving (2) and (4) reasonably small. Otherwise, the computational cost of surrogate model optimization and, especially, parameter extraction, starts playing important role in the total cost of SM optimization and may even determine it. Another problem is that the coarse-mesh EM-based model may have poor analytical properties (e.g., non-differentiability) which make them difficult to optimize [47].

The aforementioned problems can be overcome if the coarse model is created by approximating the coarse-mesh EM model data using a suitable function approximation technique. In this case, it is only necessary to evaluate the coarse-mesh EM model at a predefined set of training points, and the resulting coarse model is computationally cheap. In this work, the coarse model is built using the Cauchy rational approximation. For further reference, the coarse-mesh EM model will be denoted as $\mathbf{R}_{f\text{-}c}$.

3.2. Multi-dimensional Cauchy Approximation [42]

Cauchy interpolation technique was initially proposed in [39] for approximating the frequency response of a high frequency structure by a rational function of two polynomials. Each polynomial was a function of frequency only. The frequency response was calculated at a continuous band of frequencies using only few simulated frequencies. This approach, however, does not provide a parameterized model that can be efficiently used in optimization, tolerance analysis, statistical analysis, and yield analysis.

In [40], rational function approximation was extended to modeling of multi-dimensional EM problems. This approach is justified because even for fixed frequency, the response of many structures can exhibit strong nonlinearities with respect to material properties and different dimensions. The parameterized Cauchy model can be defined as follows. Consider a scalar system response $R_s(\mathbf{x})$, where $\mathbf{x}$ is the vector of design variables $\mathbf{x} = [x_1\ x_2\ \ldots x_n]^T$ representing, e.g., frequency, geometry parameters, material properties, etc. The response R_s can be modeled by a multi-dimensional Cauchy rational approximation of the form:

$$\bar{R}_s(\mathbf{x}) = \frac{a_0 + a_1x_1 + a_2x_2 + a_3x_1^2 + a_4x_1x_2 + a_5x_2^2 + \ldots}{b_0 + b_1x_1 + b_2x_2 + b_3x_1^2 + b_4x_1x_2 + b_5x_2^2 + \ldots} \tag{5}$$

where $\mathbf{a} = [a_0\ a_1\ \ldots a_M]^T$ and $\mathbf{b} = [b_0\ b_1\ \ldots b_M]^T$ are the unknown coefficients. The order of the polynomials in the numerator and denominator can be adjusted depending on the nonlinearity of R_s.

The target of Cauchy-based modeling is to determine the coefficients $[\mathbf{a}^T\ \mathbf{b}^T]^T$ that make the given model (5) satisfy a given set of data samples $S = \{(\mathbf{x}^i, R_s^i),\ i = 1, 2, \ldots, N_s\}$.

In [40], a recursive technique was proposed to make the solution of the model extraction feasible, which breaks down the multi-dimensional problem into a number of one-dimensional problems that are solved recursively to finally achieve the desired model [40]. This method, however, may require a large number of data samples as it utilizes a fixed number of samples in each dimension. A modified model extraction technique exploiting the total least squares (TLS) method [48] was reported in [41]. This method, however, may lead to spurious solutions that do not give a physical model [48]. It was further enhanced in [49] by employing an adaptive sampling technique to reduce the number of sample points required for a specific accuracy. An alternative formulation that promises a more robust solution to the ill-conditioned system of equations was proposed in [50]. It was applied though for only one dimensional interpolation with respect to frequency.

In this paper, we use a robust algorithm for the extraction of parameterized Cauchy model introduced in [42], which allows for an error margin in the given response data resulting in a stable formulation that is less sensitive to errors. It also implements safeguard constraints that eliminate spurious solutions. As shown in [3], the model coefficients can be found by solving the linear program of the form

$$\min_{\mathbf{v}} \mathbf{c}^T\mathbf{v} \quad \text{subject to} \quad \mathbf{A}(\delta)\mathbf{v} \le \mathbf{d} \tag{6}$$

where $\mathbf{v} = [t\ \mathbf{a}^T\ \mathbf{b}^T]^T$ is the vector of unknowns with t being an auxiliary variable introduced by the linear program. The matrix $\mathbf{A}$ depends on the set of data pairs S. The number of rows in the matrix $\mathbf{A}$ depends linearly on N_s, the vectors $\mathbf{c}$ and $\mathbf{d}$ are constant vectors whose dimensions also depend on N_s. The global optimum of the linear program (6) can always be found [42]. The vector of tolerances $\boldsymbol{\delta} = [\delta_1\ \delta_2 \ldots \delta_{Ns}]^T$ is defined as $R_i - \delta_i \le \bar{R}_s(\mathbf{x}^i) \le R_i + \delta_i$, where δ_i is allowed tolerance for the ith data sample. Here, the tolerances are identical for all samples and preset to a small value (typically 10^{-3}).

3.3. Construction of the Coarse Model

Let $X_B = \{\mathbf{x}^1, \mathbf{x}^2, \ldots, \mathbf{x}^N\}$ denotes a base set, such that the responses $\mathbf{R}_{f\text{-}c}(\mathbf{x}^j)$ are known for $j = 1, 2, \ldots, N$. Let $\mathbf{R}_{f\text{-}c}(\mathbf{x}) = [R_{f\text{-}c.1}(\mathbf{x}) \ldots R_{f\text{-}c.m}(\mathbf{x})]^T$. The Cauchy approximation coarse model $\mathbf{R}_c$

is defined as

$$\mathbf{R}_c(\mathbf{x}) = \left[\bar{R}_{f\text{-}c.1}(\mathbf{x}) \quad \bar{R}_{f\text{-}c.2}(\mathbf{x}) \quad \ldots \quad \bar{R}_{f\text{-}c.m}(\mathbf{x})\right]^T \tag{7}$$

where $\bar{R}_{f\text{-}c.i}(\mathbf{x})$ is the Cauchy model of the ith component of $\mathbf{R}_{f\text{-}c}(\mathbf{x})$ constructed as described in Section 3.2.

Note that the coarse model built as proposed here has a number of advantages:

- It is computationally cheap, smooth, and easy to optimize;
- There is no need for a circuit-equivalent model, and, consequently, no extra simulation software needs to be involved;
- The SM algorithm implementation is simpler (exploits a single EM solver),
- It is possible to apply SM for problems where finding reliable and fast coarse models is difficult or impossible (e.g., antennas). Also, the initial design obtained through optimization of the coarse-mesh EM model is usually better than the initial design that could be possibly obtained using other methods.

It should be emphasized that the Cauchy-approximation coarse model described here has certain limitations. In particular, it can be used efficiently only when only few designable parameters are considered. For larger n, the required number of evaluations of $\mathbf{R}_{f\text{-}c}$ quickly increases so that the computational cost of creating the coarse model becomes unacceptably high. Also, the coarse model is set up only once for the entire optimization process. Therefore, it has to have relatively large region of validity, and, consequently, higher-order. This increases the number of model parameters and the number of necessary training points. It also creates difficulties in ensuring the required accuracy of the Cauchy approximation. A modified version of our technique that alleviates these limitations will be addressed in a future work.

4. DESIGN OPTIMIZATION PROCEDURE

The flowchart of the proposed design optimization procedure is shown in Fig. 1. The space mapping optimization algorithm (Section 2.2) uses the Cauchy-approximation-based coarse model $\mathbf{R}_c$ created as described in Section 3.2, and also evaluates the fine model (once per iteration). The same EM solver is exploited to evaluate the fine model $\mathbf{R}_f$ and the coarse-discretization model $\mathbf{R}_{f\text{-}c}$. The latter is used both to produce the starting point for SM algorithm and to generate the data for creating $\mathbf{R}_c$.

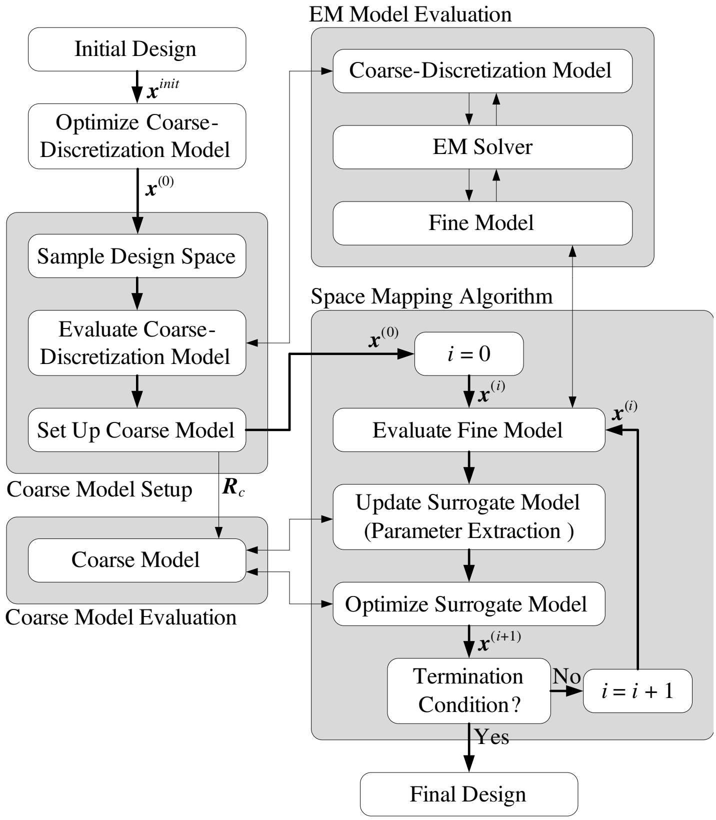


Figure 1. Flowchart of the design optimization procedure exploiting space mapping and Cauchy-approximation-based coarse models. Two main blocks are construction of the coarse model and the SM optimization algorithm. The starting point for SM optimization is the design obtained by optimizing coarse-discretization EM model $\mathbf{R}_{f\text{-}c}$. The Cauchy-approximation coarse model is set up as described in Section 3.2. The SM algorithm is implemented as described in Section 2.2. The fine model is evaluated only once per SM iteration. The same EM solver is used to generate the data necessary to build the coarse model.

5. EXAMPLES

In this section, we illustrate the operation and computational efficiency of the design optimization technique described in Section 4. We consider various examples including microstrip filters, a monopole antenna, and a microstrip-to-CPW transition. Our examples demonstrate that the proposed methodology can be used to handle a wide range of microwave structures. For all test cases, an optimized design is obtained at a cost corresponding to several evaluations of the fine model. It should be emphasized that using a coarsely discretized EM-based coarse model allows us to generate quite good starting point for the design optimization process, which would be difficult to obtain by means of other methods.

5.1. Second-order Dual-behavior Resonator Filter [51]

Consider the second-order dual-behavior resonator (DBR) filter [51] shown in Fig. 2. The design parameters are $\mathbf{x} = [L_1\ L_2\ L_3]^T$. The fine model is simulated in FEKO [52]. The total mesh number for the fine model is 1027 with simulation time of 37 minutes. The mesh number for the coarse-mesh FEKO model $\mathbf{R}_{f\text{-}c}$ is 52 meshes with a simulation time of 14 seconds. The considered response of the fine model is the modulus of the transmission coefficient, $|S_{21}|$, evaluated at 59 frequency points equally spaced over the frequency band 4.0 GHz to 6.0 GHz. The design specifications are $|S_{21}| \geq -3$ dB for 4.9 GHz $\leq \omega \leq$ 5.1 GHz, and $|S_{21}| \leq -20$ dB for 4.0 GHz $\leq \omega \leq$ 4.6 GHz and 5.4 GHz $\leq \omega \leq$ 6.0 GHz.

The initial design is $\mathbf{x}^{init} = [8.0\ \ 4.0\ \ 6.0]^T$ mm (minimax specification error +20 dB). In the first stage, the coarse-mesh model $\mathbf{R}_{f\text{-}c}$ is optimized using a pattern search with a rough grid of 0.5 mm $\times$ 0.5 mm to yield a starting point for SM optimization process. The initial design $\mathbf{x}^{(0)} = [6.5\ \ 5.0\ \ 6.0]^T$ mm (minimax specification error +9.3 dB) is obtained after 17 evaluations of $\mathbf{R}_{f\text{-}c}$. Fig. 3 shows the

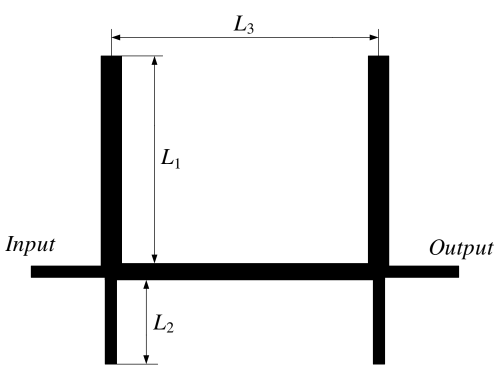


Figure 2. Geometry of the dual-behavior resonator filter [51].

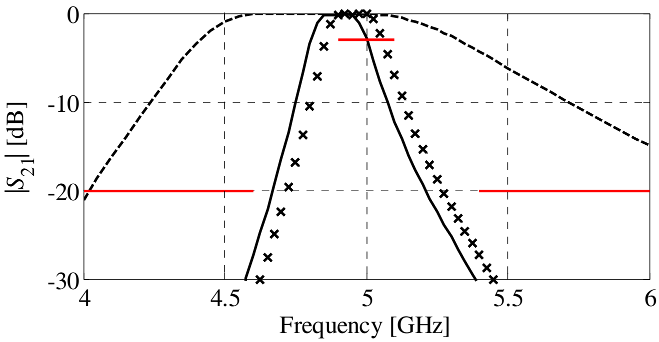


Figure 3. DBR filter: fine model responses at the initial design $\mathbf{x}^{init}$ (dashed line) and at the optimized design $\mathbf{x}^{(0)}$ of the coarse-mesh FEKO model $\mathbf{R}_{f\text{-}c}$ (solid line), as well as the response of $\mathbf{R}_{f\text{-}c}$ at $\mathbf{x}^{(0)}$ ($\times$).

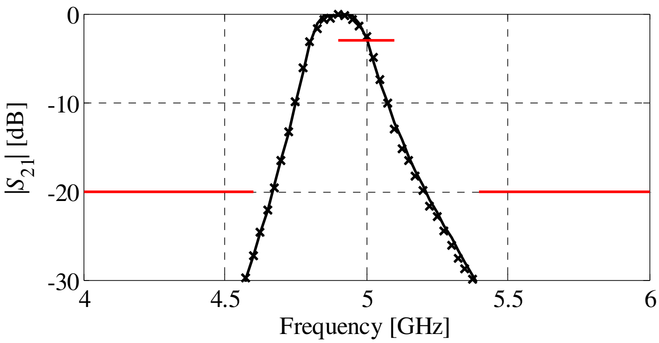


Figure 4. DBR filter: fine model response (solid line) and the space-mapped coarse model response ($\times$) at optimized design of the coarse-mesh FEKO model $\mathbf{R}_{f\text{-}c}$, $\mathbf{x}^{(0)}$.

fine model responses at $\mathbf{x}^{init}$ and $\mathbf{x}^{(0)}$ as well as the response of $\mathbf{R}_{f\text{-}c}$ at $\mathbf{x}^{(0)}$. The Cauchy-approximation-based coarse model $\mathbf{R}_c$ (7) is constructed in the region $6.3\,\text{mm} \leq L_1 \leq 6.7\,\text{mm}$, $4.8\,\text{mm} \leq L_2 \leq 5.2\,\text{mm}$, $4\,\text{mm} \leq L_3 \leq 8\,\text{mm}$ using $4^3 = 64$ evaluations of $\mathbf{R}_{f\text{-}c}$ allocated on the rectangular grid. The DBR filter was optimized using the SM algorithm with the input and output SM surrogate of the form $\bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{p}) = \bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{c}, \mathbf{d}) = \mathbf{R}_c(\mathbf{x} + \mathbf{c}) + \mathbf{d}$. Fig. 4 shows the response of $\mathbf{R}_f$ and space-mapped $\mathbf{R}_c$ at $\mathbf{x}^{(0)}$.

The design obtained after two SM iterations is $\mathbf{x}^{(2)} =$

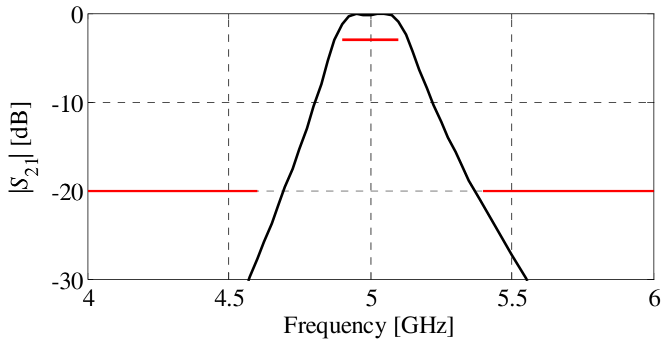


Figure 5. DBR filter: fine model response at the final design $\mathbf{x}^{(2)}$.

Table 1. Computational cost of optimizing the second-order DBR filter.

Algorithm Component	Model Involved	Number of Model Evaluations	Absolute Time [min]	Relative Time
Optimization of $\mathbf{R}_{f\text{-}c}$	$\mathbf{R}_{f\text{-}c}$	17	4	0.1
Setting up the Cauchy model $\mathbf{R}_c$	$\mathbf{R}_{f\text{-}c}$	64	15	0.4
Evaluation of $\mathbf{R}_f$	$\mathbf{R}_f$	3*	111	3.0
Total optimization time	N/A	N/A	130	3.5

* Excluding evaluation of the fine model at initial design.

$[6.52\ 4.86\ 4.00]^T$ mm. The fine model minimax specification error at $\mathbf{x}^{(2)}$ is -1.8 dB (Fig. 5). Table 1 summarizes the computational cost of the optimization: the total optimization time corresponds to only 3.5 evaluations of $\mathbf{R}_f$. It should be noted that further reduction of the computational cost of the optimization process could be achieved by reducing the number of frequency samples for the coarsely-discretized model $\mathbf{R}_{f\text{-}c}$.

5.2. Monopole Planar Antenna

We also consider the planar monopole antenna shown in Fig. 6(a). The input 50 ohm microstrip line with a conductor width of $W_m = 3.45$ mm is excited at the substrate periphery. The substrate dielectric is described by the general second order dispersion model [53] fitting permittivity and loss tangent of FR408 laminates [54]. Metal thickness, t, is 0.035 mm. The design parameters are $\mathbf{x} = [L_t\ L_o\ L_{GND}]^T$. The other variables are fixed at $L_p = 16.0$ mm, $W_p = 18$ mm, $L_s = 3.0$ mm, and $W_s = 2.0$ mm.

The fine model is simulated in CST Microwave Studio [53] using the transient solver and a fine subgrid spatial discretization (247,319 mesh cells). The simulation time for $\mathbf{R}_f$ is 48 min. The coarse-discretization model $\mathbf{R}_{f\text{-}c}$ has 8,963 mesh cells with a simulation time of only 55 s. In both models the background medium (free space) is truncated by PMLs (8 layers in the fine model and 4 layers in the coarse model). The response of the fine model is the modulus of the reflection coefficient $|S_{11}|$ over the frequency band 2.0 GHz to 9.0 GHz. The

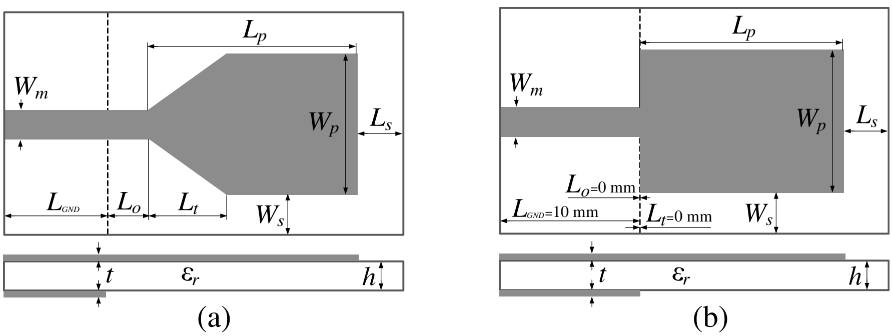


Figure 6. Monopole antenna: (a) frame geometry for optimization; (b) geometry of the initial design $\mathbf{x}^{init}$.

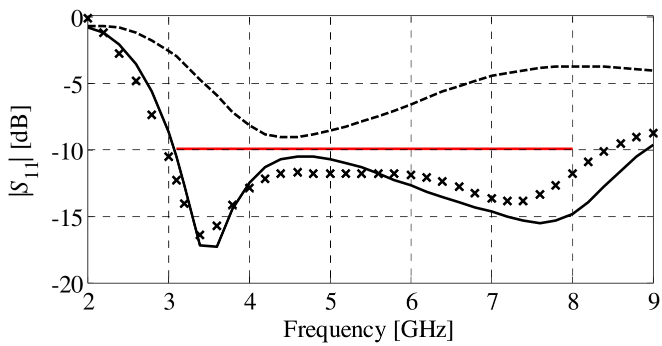


Figure 7. Monopole antenna: fine model responses at the initial design $\mathbf{x}^{init}$ (dashed line) and at the optimized design $\mathbf{x}^{(0)}$ of the coarse-discretization CST model (solid line), and the response of $\mathbf{R}_{f\text{-}c}$ at $\mathbf{x}^{(0)}$ ($\times$).

design specifications are $|S_{11}| \leq -10\,\mathrm{dB}$ for $3.1\,\mathrm{GHz} \leq \omega \leq 8.0\,\mathrm{GHz}$.

The initial design is $\mathbf{x}^{init} = [0\ 0\ 10.0]^T$ mm (minimax specification error $+7\,\mathrm{dB}$). The starting point for the SM algorithm, $\mathbf{x}^{(0)} = [7\ 0\ 14]^T$ mm, is obtained by grid-search optimization of $\mathbf{R}_{f\text{-}c}$ on the $1.0\,\mathrm{mm} \times 1.0\,\mathrm{mm}$ grid. The computational cost is 28 evaluations of $\mathbf{R}_{f\text{-}c}$. Fig. 7 shows the fine model responses at $\mathbf{x}^{init}$ and $\mathbf{x}^{(0)}$ as well as the response of $\mathbf{R}_{f\text{-}c}$ at $\mathbf{x}^{(0)}$. The Cauchy-based coarse model $\mathbf{R}_c$ is constructed in the region $3.0\,\mathrm{mm} \leq L_t \leq 8.0\,\mathrm{mm}$, $-1.0\,\mathrm{mm} \leq L_o \leq 1.0\,\mathrm{mm}$, $12.0\,\mathrm{mm} \leq L_{GND} \leq 16.0\,\mathrm{mm}$ using $5^3 = 125$ evaluations of the coarse-discretization model $\mathbf{R}_{f\text{-}c}$.

Because of limited accuracy of the coarse-discretization model, the input SM is not able to provide sufficient alignment between the coarse and fine models. Therefore, a variation of output SM, so-called adaptive response correction technique [37] was used as the optimization engine in this case. Adaptive response correction is a generalization of the output SM that exploits a design-variable dependent response correction term that tracks the changes of the coarse model that occur during the coarse model optimization and maps these changes into the surrogate model [37].

The design obtained after two iterations is $\mathbf{x}^{(2)} = [3.472\ 0.708\ 15.523]^T$ mm. The fine model minimax specification error at $\mathbf{x}^{(2)}$ is $-2.2\,\mathrm{dB}$ (Fig. 8), i.e., we have $|S_{11}| < -12\,\mathrm{dB}$ from 3.1 GHz to 8 GHz. Table 2 summarizes the computational cost. The total optimization time corresponds to less than 6 evaluations of the fine model.

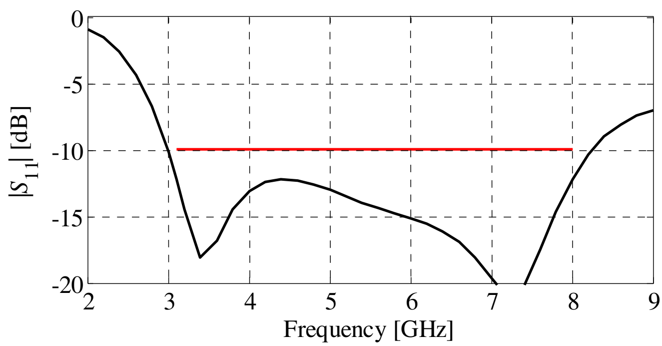
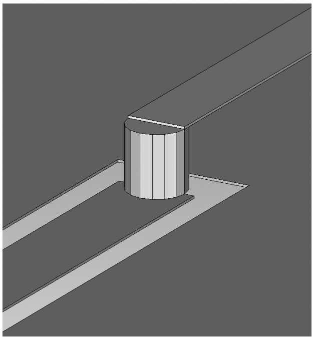
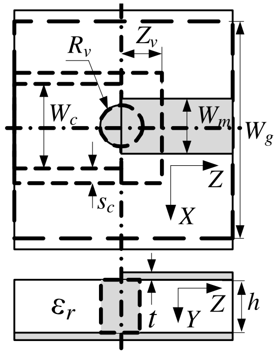


Figure 8. Monopole antenna: fine model response at the final design $\mathbf{x}^{(2)}$.



(a)



(b)

Figure 9. Common ground microstrip-to-CPW transition: (a) 3D view (substrate not shown); (b) layout views.

Table 2. Computational cost of optimizing the monopole antenna.

Algorithm Component	Model Involved	Number of Model Evaluations	Absolute Time [min]	Relative Time
Optimization of $\mathbf{R}_{f\text{-}c}$	$\mathbf{R}_{f\text{-}c}$	28	26	0.5
Setting up the Cauchy model $\mathbf{R}_c$	$\mathbf{R}_{f\text{-}c}$	125	115	2.4
Evaluation of $\mathbf{R}_f$	$\mathbf{R}_f$	3*	144	3.0
Total optimization time	N/A	N/A	285	5.9

* Excluding evaluation of the fine model at initial design.

5.3. Common Ground Microstrip-to-coplanar Waveguide Transition

A microstrip-to-coplanar waveguide (CPW) transition is shown in Fig. 9. The microstrip and CPW are interfaced through a single via connecting the signal traces with the transmission lines (TLs) sharing the same ground plane [55], see Fig. 9. Unlike in [55], the design geometry in our example is defined with the CPW ending on the rectangular slot and the straight barrel via with no pads. The lengths of the input TLs are 15.0 mm each. We use 0.635 mm thick RT6010 substrate. The dielectric is described with the 1st order Debye model. The metal has a conductivity of 5.7e8 S/m and a thickness of 0.0254 mm. The remaining dimensions are as follows: $W_m = 0.6$ mm, $W_c = 0.8$ mm, $s_c = 0.3$ mm, and $W_g = 9.4$ mm. The low frequency

TL impedances are 50 ohm. The transition is simulated using the CST MWS transient solver [53]. The fine model $\mathbf{R}_f$ has 1,254,528 cells (at the initial design) with a simulation time of approximately 50 min. The coarse discretization model $\mathbf{R}_{f\text{-}c}$ has 393,984 mesh cells with a simulation time of 640 s.

The design objective is to obtain $|S_{11}| \leq -25\,\text{dB}$ and $|S_{22}| \leq -25\,\text{dB}$ from DC to 20 GHz. The design variables are $\mathbf{x} = [Z_v\ R_v]^T$ with a starting point $\mathbf{x}^{(0)} = [0.5\ 0.3]^T$. Because of the fact that the coarsely discretized model $\mathbf{R}_{f\text{-}c}$ is relatively expensive (only 5 times cheaper than the fine model), the starting point for SM algorithm, $\mathbf{x}^{(0)} = [0.4\ 0.1296]^T$ mm, is obtained by optimizing even coarser model $\mathbf{R}_{f-cc}$ (69,888 mesh cells, simulation time is 116 s). The computational cost is 31 evaluations of $\mathbf{R}_{f-cc}$. Fig. 10 shows the fine model responses at $\mathbf{x}^{init}$ and $\mathbf{x}^{(0)}$ as well as the response of $\mathbf{R}_{f\text{-}c}$ at $\mathbf{x}^{(0)}$. The second-order Cauchy-based coarse model $\mathbf{R}_c$ is constructed in the region defined by ±10% deviation from $\mathbf{x}^{(0)}$. A total of 12 evaluations of the model $\mathbf{R}_{f\text{-}c}$ allocated on the uniform 3×4 grid are utilized within this region.

As we can observe in Fig. 10, the model responses are relatively complex, however, overall accuracy of the coarsely discretized model $\mathbf{R}_{f\text{-}c}$ is good. Therefore, we use the output-SM-based surrogate model of the form $\bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{p}) = \bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{d}) = \mathbf{R}_c(\mathbf{x}) + \mathbf{d}$ with the vector $\mathbf{d}$ calculated, at ith iteration, as $\mathbf{d} = \mathbf{R}_f(\mathbf{x}^{(i)}) - \mathbf{R}_c(\mathbf{x}^{(i)})$. The optimization process is terminated after two iterations and yields the design $\mathbf{x}^{(2)} = [0.354\ \ 0.1274]^T$ mm. The fine model minimax

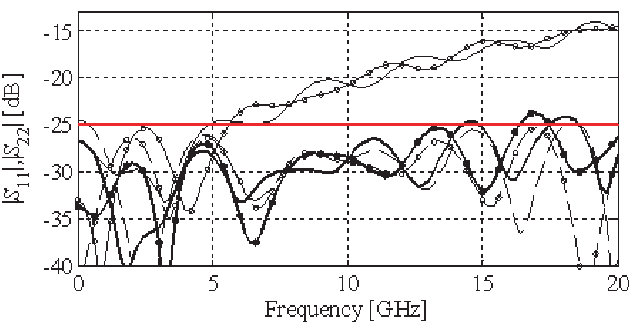


Figure 10. Common ground transition microstrip-to-CPW: responses of the fine model at the initial design $\mathbf{x}^{init}$ (thin solid line) and at the optimized design $\mathbf{x}^{(0)}$ of the coarse-discretization model $\mathbf{R}_{f-c}$ (thick solid line), as well as the response of $\mathbf{R}_{f-c}$ at $\mathbf{x}^{(0)}$ (dashed line). $|S_{22}|$ distinguished from $|S_{11}|$ using circles.

specification error at $\mathbf{x}^{(2)}$ is -1.8 dB (Fig. 11), i.e., we have $|S_{11}|$, $|S_{22}|$ less then about -27 dB in the entire frequency range of interest (DC to 20 GHz). The computational cost is summarized in Table 3. The total optimization time corresponds to less than 7 evaluations of the fine model.

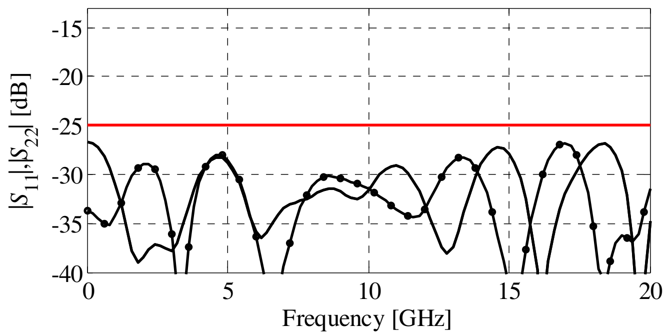


Figure 11. Common ground transition microstrip-to-CPW: fine model response at the final design $\mathbf{x}^{(2)}$. $|S_{22}|$ distinguished from $|S_{11}|$ using circles.

Table 3. Computational cost of optimizing the common ground microstrip-to-CPW transition.

Algorithm Component	Model Involved	Number of Model Evaluations	Absolute Time [min]	Relative Time
Optimization of $\mathbf{R}_{f\text{-}c}$#	$\mathbf{R}_{f\text{-}cc}$	31	60	1.2
Setting up the Cauchy model $\mathbf{R}_c$	$\mathbf{R}_{f\text{-}c}$	12	128	2.6
Evaluation of $\mathbf{R}_f$	$\mathbf{R}_f$	3*	150	3.0
Total optimization time	N/A	N/A	338	6.8

* Excluding evaluation of the fine model at initial design.

\# This step was performed using a very-coarse-discretization model $\mathbf{R}_{f\text{-}cc}$ (69,888 mesh cells, simulation time 116 s).

5.4. Microstrip Bandpass Filter with Two Transmission Zeros [56]

Our last example is a microstrip bandpass filter with two transmission zeros [56] shown in Fig. 12. The design parameters are $x = [L\, s\, d]^T$. We also have $L = L_1 = L_2$, and $g = 0.1$ mm. The fine model is simulated in FEKO [52]. The total mesh number for $\mathbf{R}_f$ is 1084 with a simulation time of 24 min. The total mesh number for the coarse-mesh FEKO model $\mathbf{R}_{f\text{-}c}$ is 150 meshes corresponding to a simulation time of 40 seconds. The design specifications are $|S_{21}| \leq -20$ dB for $1.5\,\text{GHz} \leq \omega \leq 1.8\,\text{GHz}$, $|S_{21}| \geq -1$ dB for $1.95\,\text{GHz} \leq \omega \leq 2.05\,\text{GHz}$, and $|S_{21}| \leq -20$ dB for $2.2\,\text{GHz} \leq \omega \leq 2.5\,\text{GHz}$.

The initial design is $\mathbf{x}^{init} = [7.5\ 0.2\ 2.0]^T$ mm with a minimax

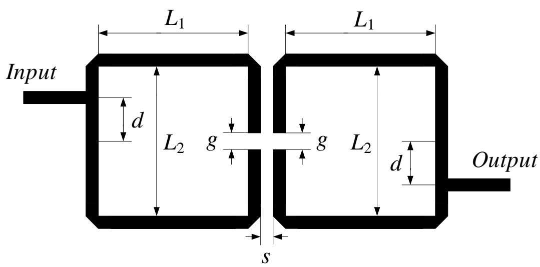


Figure 12. Microstrip bandpass filter with two transmission zeros: geometry [56].

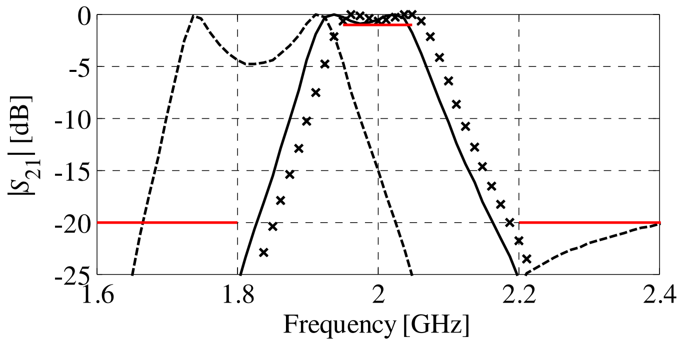


Figure 13. Bandpass filter with two transmission zeros: fine model responses at the initial design $\mathbf{x}^{init}$ (dashed line) and at the optimized design $\mathbf{x}^{(0)}$ of the coarse-mesh FEKO model $\mathbf{R}_{f\text{-}c}$ (solid line), as well as the response of $\mathbf{R}_{f\text{-}c}$ at $\mathbf{x}^{(0)}$ ($\times$).

specification error of $+25\,\mathrm{dB}$. The starting point for the SM optimization algorithm, $\mathbf{x}^{(0)} = [6.953\ 0.398\ 2.102]^T$ mm (specification error $+9.3\,\mathrm{dB}$), is obtained by optimizing $\mathbf{R}_{f\text{-}c}$. A total of 97 evaluations of the coarsely discretized EM model are required. The fine model responses at $\mathbf{x}^{init}$ and $\mathbf{x}^{(0)}$ as well as the response of $\mathbf{R}_{f\text{-}c}$ at $\mathbf{x}^{(0)}$ are shown in Fig. 13. The Cauchy-based coarse model is constructed in the region $\mathbf{x}^{(0)} \pm [0.1\ 0.1\ 0.1]^T$ mm using $4 \times 4 \times 3 = 48$ evaluations of $\mathbf{R}_{f\text{-}c}$ allocated on the rectangular grid. The filter is then optimized using the SM algorithm with the frequency and output SM surrogate of the form $\bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{p}) = \bar{\mathbf{R}}_s(\mathbf{x}, \mathbf{F}, \mathbf{d}) = \mathbf{R}_{c.f}(\mathbf{x}, \mathbf{F}) + \mathbf{d}$ [13], where $\mathbf{R}_{c.f}$ is a frequency-mapped coarse model (cf. Section 2.2). The design obtained after two SM iterations is $\mathbf{x}^{(2)} = [6.888\ 0.418\ 2.2]^T$ mm with a minimax specification error of $-0.6\,\mathrm{dB}$. The fine model at this response is shown in Fig. 14. The total computational cost of the optimization (Table 4) corresponds to 7 evaluations of the fine model. Similarly as in the first example, further reduction of the computational cost of the optimization process could be achieved by reducing the number of frequency samples for the coarsely-discretized model $\mathbf{R}_{f\text{-}c}$.

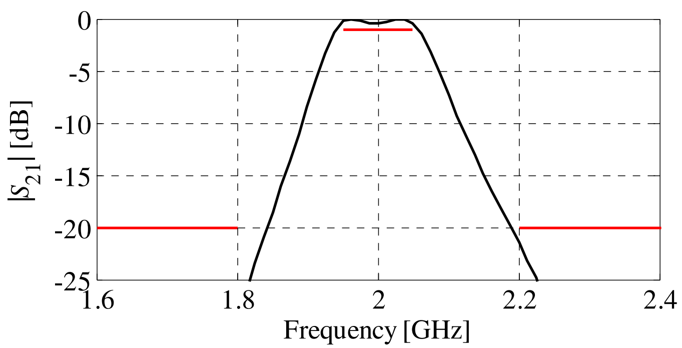


Figure 14. Bandpass filter with two transmission zeros: fine model response at the final design $\mathbf{x}^{(2)}$.

5.5. Discussion

As mentioned in the introduction and in Section 3, the main novelty of the proposed technique is the way of creating the coarse model for the space mapping optimization process. Because the coarse model is built from coarsely-discretized EM model data, our technique is quite versatile and allows us to handle a large variety of microwave structures as illustrated above. This is not the case for standard SM which typically exploits equivalent-circuit models and

Table 4. Computational cost of optimizing the bandpass filter with two transmission zeros.

Algorithm Component	Model Involved	Number of Model Evaluations	Absolute Time [min]	Relative Time
Optimization of $\mathbf{R}_{f\text{-}c}$	$\mathbf{R}_{f\text{-}c}$	97	64	2.7
Setting up the Cauchy model $\mathbf{R}_c$	$\mathbf{R}_{f\text{-}c}$	48	32	1.3
Evaluation of $\mathbf{R}_f$	$\mathbf{R}_f$	3*	72	3.0
Total optimization time	N/A	N/A	168	7.0

* Excluding evaluation of the fine model at initial design.

has difficulty with handling EM-based coarse models directly [47]. As the accuracy of Cauchy-approximation-based coarse models is typically better than that of equivalent-circuit ones or the models using analytical formulas, the proposed technique usually yields a satisfactory design after just two or three iterations of the SM algorithm. The algorithm exploiting equivalent-circuit model typically needs more iterations [13, 14]. However, the computational cost of the optimization process is similar to that of SM exploiting equivalent circuits because of the additional overhead related to the coarse model creation. Nevertheless, the most important advantage of the proposed technique is its versatility: it allows application of space mapping for cases where reliable circuit-based or analytical coarse models are not available (cf. Sections 5.2 and 5.3).

6. CONCLUSION

An efficient implementation of space mapping optimization algorithm has been presented. This novel implementation exploits the multi-dimensional Cauchy approximation of coarse-mesh EM simulation data for creating the coarse model. The proposed approach is particularly suitable for problems where it is difficult or impossible to find a circuit-equivalent or analytical coarse models. These include, among others, the design of UWB antennas and substrate integrated circuits. The efficiency of our technique is demonstrated through the design optimization of two microstrip filters, a monopole antenna, as well as a microstrip-to-CPW transition. Satisfactory designs are obtained at the cost of a few EM simulations of the respective structures.

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