EM-Based Surrogate Modeling and Design Exploiting Implicit, Frequency and Output Space Mappings

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***Abstract* — We present a significant improvement to the novel implicit space mapping (ISM) concept for EM-based microwave modeling and design. ISM calibrates a suitable coarse (surrogate) model against a fine model (full-wave EM simulation) by relaxing certain coarse model preassigned parameters. Based on an explanation of residual response misalignment, our new approach further fine-tunes the surrogate by exploiting an "output space" mapping (OSM). An accurate design of an HTS filter, easily implemented in Agilent ADS, emerges after only four EM simulations using ISM and OSM with sparse frequency sweeps. For the first time also, frequency space mapping is implemented in an ISM framework.**

I. INTRODUCTION

The space mapping (SM) concept exploits coarse models (usually computationally fast circuit-based models) to align with fine models (typically CPU intensive full-wave EM simulations) [1]-[7]. The novel implicit space mapping (ISM) concept exploits preassigned parameters such as the dielectric constant and substrate height [5]. In the parameter extraction process these parameters were exploited to match the fine model.

This paper presents a significant improvement to ISM. Based on an explanation of residual misalignment close to the optimal fine model solution, where a classical Taylor model is seen to be better than SM, our new approach further fine-tunes the surrogate by exploiting an "output space" mapping (OSM).

The OSM we suggest is very simple to apply. It is consistent with the idea of pre-distorting design specifications to permit the fine model greater latitude—anticipating violations and making the specifications correspondingly stricter. Our new OSM exploits this to fine tune the surrogate model. An accurate design of an HTS filter, easily implemented in Agilent ADS [8], emerges after only four EM simulations using ISM and OSM with sparse frequency sweeps (two iterations of ISM, followed by one application of the OSM).

In this paper we also broaden the concept of auxiliary (preassigned) parameters to frequency transformation parameters. See, e.g., [2]. We embed a linear mapping to relate the actual (fine model) frequency and the transformed (coarse model) frequency into the surrogate.

II. FREQUENCY IMPLICIT SPACE MAPPING

In each iteration, we extract selected frequency transforming preassigned parameters to match the updated surrogate model with the fine model. Then we assign its optimized design parameters to the fine model. We repeat this process until the fine model response is sufficiently close to the target (optimal original coarse model) response.

Algorithm

Step 1 Select a coarse model and a fine model

Step 2 Select the frequency transformation and initialize associated preassigned parameters. For example, we can use a linear transformation of frequency $\omega_c = \sigma\omega + \delta$ [2]. The preassigned parameters are then $[\sigma\ \delta]^T$, initialized as $[1\ 0]^T$

Step 3 Optimize the coarse model (initial surrogate) w.r.t. design parameters

Step 4 Simulate the fine model at this solution

Step 5 Terminate if a stopping criterion is satisfied, e.g., response meets specifications

Step 6 Apply parameter extraction (PE) to extract frequency transforming preassigned parameters

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Step 7 Reoptimize the "frequency mapped coarse model" (surrogate) w.r.t. design parameters (or evaluate the inverse mapping if it is available)

Step 8 Go to Step 4

Examples involving frequency implicit space mapping have been investigated.

III. OUTPUT SPACE MAPPING (OSM)

The original design problem is

$$x_f^* = \arg \min_{x_f} U(R_f(x_f)) \tag{1}$$

Here, the fine model response vector is denoted by $R_f \in \Re^{m\times 1}$, e.g., $|S_{11}|$ at selected frequency points ω; m is the number of sample points; the fine model point is denoted $x_f \in \Re^{n\times 1}$, where n is the number of design parameters. U is a suitable objective function. x_f^* is the optimal design.

The OSM addresses residual misalignment between the optimal coarse model response and the true fine model optimum response $R_f(x_f^*)$. (In space mapping, an exact match between the fine model and the mapped coarse model is unlikely.) For example, a coarse model such as $R_c = x^2$ will never match the fine model $R_f = x^2 - 2$ around its minimum with any mapping $x_c = P(x_f)$, $x_c, x_f \in \Re$. An "output" or response mapping can overcome this deficiency by introducing a transformation of the coarse model response based on a Taylor approximation [9].

Fig. 1 depicts model effectiveness plots [10] for a two-section capacitively loaded impedance transformer [10] at the final iterate $x_f^{(i)}$, approximately $[74.23 \quad 79.27]^T$.

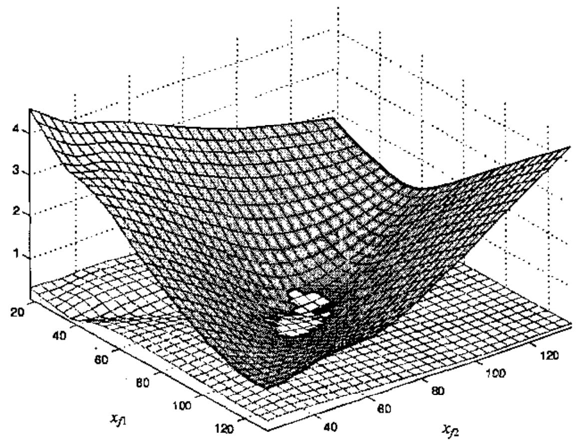


Fig. 1. Error plots for a two-section capacitively loaded impedance transformer [10] exhibiting the quasi-global effectiveness of space mapping (light grid) versus a classical Taylor approximation (dark grid). See text.

Centered at $h = 0$, the light grid shows $\| R_f(x_f^{(i)} + h) - R_c(L_p(x_f^{(i)} + h)) \|$. This represents the deviation of the mapped coarse model (using the Taylor approximation to the mapping, i.e., a linearized mapping) from the fine model. The dark grid shows $\| R_f(x_f^{(i)} + h) - L_f(x_f^{(i)} + h) \|$. This is the deviation of the fine model from its classical Taylor approximation. It is seen that the Taylor approximation is most accurate close to $x_f^{(i)}$ whereas the mapped coarse model is best over a large region.

Output space mapping aims at establishing a mapping O between R_s (output mapped surrogate response) and R_c (mapped coarse model response)

$$R_s = O(R_c) \tag{2}$$

such that

$$R_s \approx R_f \tag{3}$$

We can predict the fine model solution using this surrogate.

IV. IMPLICIT AND OUTPUT SPACE MAPPING ALGORITHM

Our proposed algorithm starts with ISM [5]. If the calibration (PE) step in [5] does not improve the match, which will eventually happen close to x_f^*, then we create a surrogate with response R_s. In this paper we consider a mapping of the form

$$R_s = O(R_c) \triangleq R_c(x_c, x) + diag\{\lambda_1, \lambda_2, \cdots, \lambda_m\} \Delta R \tag{4}$$

where

$$\Delta R = R_f(x_f) - R_c(x_c^{*(i)}, x) \tag{5}$$

is the residual between the mapped coarse model response after PE and the fine model response, and where the λ_i are weighting parameters [10].

The coarse model parameters x_c are obtained by optimizing the surrogate (4) to give

$$x_c^{*(i+1)} \triangleq \arg \min_{x_c} U(O(R_c(x_c, x))) \tag{6}$$

Then we predict an update to the fine model solution as

$$x_f = x_c^{*(i+1)} \tag{7}$$

V. HTS FILTER EXAMPLE

We consider the HTS bandpass filter of [11]. The physical structure is shown in Fig. 2. Design variables are

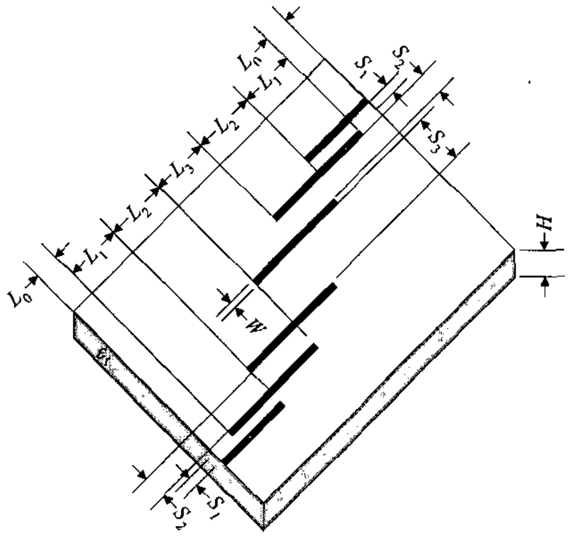


Fig. 2. The HTS filter [11] example.

the lengths of the coupled lines and the separations between them, namely,

$$x_f = [S_1\ S_2\ S_3\ L_1\ L_2\ L_3]^T$$

The substrate used is lanthanum aluminate with ε_r= 23.425, H= 20 mil and substrate dielectric loss tangent of 0.00003. The length of the input and output lines is L_0=50 mil; the lines are of width W= 7 mil. We choose ε_r and H as the preassigned parameters of interest, thus x_0=[20 mil 23.425]^T. The design specifications are

$|S_{21}| \le 0.05$ for $\omega \ge 4.099$ GHz and for $\omega \le 3.967$ GHz

$|S_{21}| \ge 0.95$ for 4.008 GHz $\le \omega \le$ 4.058 GHz

This corresponds to 1.25% bandwidth.

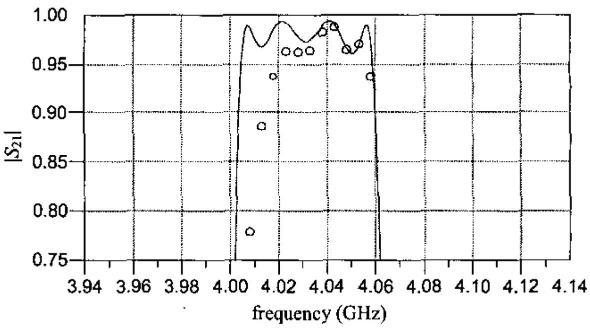
TABLE I
OPTIMIZABLE PARAMETER VALUES OF THE HTS FILTER

Parameter	Initial solution	Solution reached by the ISM algorithm	Solution by the ISM and OSM
L_1	189.65	187.10	178.28
L_2	196.03	191.30	200.86
L_3	189.50	186.97	177.99
S_1	23.02	22.79	20.18
S_2	95.53	93.56	86.15
S_3	104.95	104.86	85.17
all values are in mils			

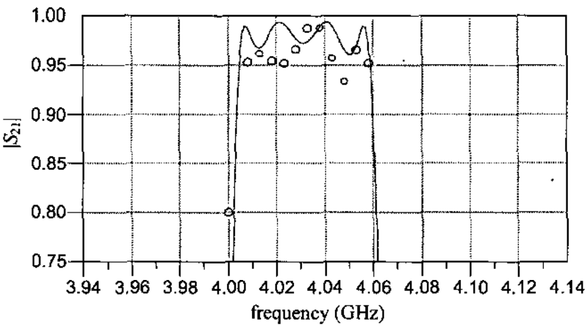
Our Agilent ADS [8] coarse model consists of empirical models for single and coupled microstrip transmission lines, with ideal open stubs. The preassigned parameter vector is

$$x = [\varepsilon_{r1}\ H_1\ \varepsilon_{r2}\ H_2\ \varepsilon_{r3}\ H_3]^T$$

which consists of the dielectric constants and substrate heights of the 5 coupled microstrip lines (note the symmetry of the structure). The fine model is simulated by Agilent Momentum [8]. The relevant responses at the initial solution are shown in Fig. 4(a), where we notice severe misalignment. Figs. 3(a) and 4(b) show the response after running the ISM algorithm. After two iterations (3 fine model simulations), the calibration step does not improve further, as seen in Fig. 4(b). Since we believe we are close to the true optimal solution, we introduce the output space mapping and use the output space mapped response in (4) with λ_i = 0.5, i = 1, 2, ..., m as initial values. After one iteration of OSM, we obtain the improved response shown in Fig. 3(b) and Fig.4(c). This is achieved in only 4 fine model evaluations. The total time taken is 35 min (one fine model simulation takes approximately 9 min on an Athlon 1100 MHz). Table I shows initial and final designs. The initial and final



(a)



(b)

Fig. 3. The fine (○) and optimal coarse model (—) magnitude responses of the HTS filter, at the final iteration using ISM (a), followed by one iteration of OSM (b).

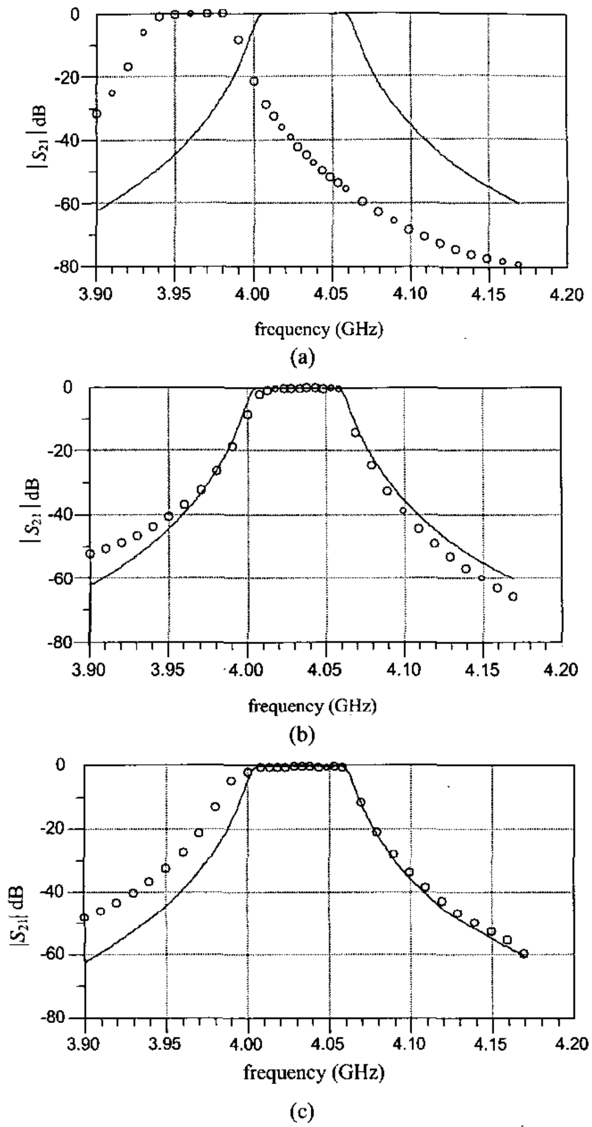


Fig. 4. The fine (○) and optimal coarse model (—) responses in dB at the initial solution (a), at the final iteration using ISM (b), and at the final iteration using ISM and OSM (c).

preassigned parameters of the calibrated coarse model of the HTS filter have the same values as in [5], i.e., $x^{(3)} = [24.404 \quad 19.80 \text{ mil} \quad 24.245 \quad 19.05 \text{ mil} \quad 24.334 \quad 19.00 \text{ mil}]^T$.

The PE uses real and imaginary S parameters and the ADS quasi-Newton optimization algorithm, while coarse model and OSM surrogate optima are obtained by the ADS minimax optimization algorithm.

VI. Conclusions

We propose significant improvements to implicit space mapping for EM-based modeling and design. Based on an explanation of residual misalignment, our new approach further fine-tunes the surrogate by exploiting an "output space" mapping. The required HTS filter models and OSM are easily implemented by Agilent ADS and Momentum with no matrices to keep track of. An accurate HTS microstrip filter design solution emerges after only four EM simulations with sparse frequency sweeps.

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