Fast Design Optimization of Microwave Structures Using Co-Simulation-Based Tuning Space Mapping

Slawomir Koziel[1] and John W. Bandler[2]

Engineering Optimization & Modeling Center, School of Science and Engineering
Reykjavik University, IS-101 Reykjavik, Iceland
koziel@ru.is

Simulation Optimization Systems Research Laboratory
Department of Electrical and Computer Engineering, McMaster University
Hamilton, ON, Canada L8S 4K1
bandler@mcmaster.ca

Abstract **─** Tuning space mapping (TSM) expedites efficient design optimization of microwave circuits by replacing sections in the electromagnetic (EM) model with corresponding sections of designable equivalent elements. A key assumption of TSM is that these designable elements can replace their respective EM model sections without introducing significant distortion in the structure's response. This can be achieved through the co-calibrated ports technique introduced in Sonnet ***em***. Here, we generalize the TSM algorithm. A tuning model is constructed by simulating the EM model sections separately and connecting them with the tuning components through a co-simulation process. This allows us to implement the TSM algorithm with any EM simulator. The response misalignment between the original structure and the tuning model is reduced using classical space mapping. The proposed algorithm is illustrated through the design of two microstrip filters simulated in FEKO.

Index Terms **─** Computer-aided design (CAD), co-simulation, electromagnetic simulation, engineering design optimization, tuning space mapping.

I. INTRODUCTION

Surrogate-based optimization methodology [1, 2], particularly space mapping (SM) [3-8], facilitates the efficient simulation-based design of CPU intensive structures. A recent development in microwave space mapping technology is tuning space mapping (TSM) [9, 10], which combines SM with the tuning concept widely used in microwave engineering [11, 12].

TSM requires a so-called tuning model, which is constructed by introducing circuit-theory based components (e.g., capacitors, coupled-line models) into the structure under consideration (fine model). Some parameters of these components are selected as tunable. The corresponding tuning model is updated and optimized with respect to the tuning parameters. In the calibration process, optimal values of the tuning parameters are transformed into an appropriate modification of the design variables, which are then assigned to the fine model. Because the tuning model is based on an "image" of the fine model, its generalization capability is usually better than one of the standard SM surrogate models [3]. It results in a smaller number of fine model evaluations required to find a satisfactory design (typically 1 to 3 iterations [9]).

Key to TSM is that the designable components of the tuning model represent their respective EM model sections without introducing significant distortion of the structure's response. This can be achieved using the co-calibrated ports technique introduced in Sonnet ***em*** [13].

In this paper, we generalize the TSM algorithm by constructing the tuning model through separate simulation of the relevant EM model sections and combining them with circuit-theory-based tuning components through a co-simulation process [14, 15]. The unavoidable

Submitted On: August 18, 2010
Accepted On: March 9, 2011

response misalignment between the original structure and the tuning model is reduced using classical space mapping.

Our approach allows us to implement the TSM algorithm using any EM simulator. Here, we exploit FEKO [16].

The robustness of our technique is demonstrated by the optimization of two microstrip filters. Good designs are obtained after just a few EM simulations of the respective structures. Here, a comprehensive numerical comparison with other optimization techniques is provided, including gradient-based and derivative-free algorithms as well as space mapping [6].

II. CO-SIMULATION-BASED TUNING SPACE MAPPING

In this section, we formulate the optimization problem (Section II.*A*), describe the tuning space mapping algorithm (Section II.*B*), and explain the construction of the proposed co-simulation-based tuning model (Section II.*C*).

A. Design optimization problem

The design optimization problem is formulated as

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

where $\boldsymbol{R}_f \in R^m$ denotes the response vector of a fine model of a device of interest; $\boldsymbol{x} \in R^n$ is a vector of design variables, and U is a scalar merit function, e.g., a minimax function with upper and lower specifications. Vector $\boldsymbol{x}_f^*$ is the optimal design to be determined.

B. Tuning space mapping algorithm

We adopt the TSM algorithm with embedded surrogates (ETSM) [10]. ETSM involves the tuning model $\boldsymbol{R}_t$ where certain designable sub-sections of the structure of interest are replaced by suitable surrogates [10], preferably distributed elements with physical dimensions corresponding to those of the fine model. After a space-mapping-based alignment procedure, the tuning model is matched to the fine model. Because critical fine-model couplings are preserved (or represented through *S*-parameters) in the tuning model, $\boldsymbol{R}_t$ is expected to be a good surrogate of the fine model. Using the design parameters of the embedded surrogates, we subsequently optimize the tuning model to satisfy the given design specifications. The resulting design parameters become our next fine model iterate. A conceptual illustration of the embedded surrogates is shown in Fig. 1.

The iteration of the ETSM algorithm consists of two steps: alignment of the tuning model with the fine model and the optimization of the tuning model. First, based on fine model data at the current design $\boldsymbol{x}^{(i)}$, the current tuning model $\boldsymbol{R}_t^{(i)}$ is built with appropriate surrogate elements replacing certain fine model sections. The tuning model response may not agree with the response of the original fine model at $\boldsymbol{x}^{(i)}$. We align these models through the parameter extraction process

$$\boldsymbol{p}^{(i)} = \arg\min_{\boldsymbol{p}} \left\| \boldsymbol{R}_f(\boldsymbol{x}^{(i)}) - \boldsymbol{R}_t^{(i)}(\boldsymbol{x}^{(i)}, \boldsymbol{p}) \right\|, \tag{2}$$

where $\boldsymbol{p}$ represents the parameters of the tuning model used in the alignment process. These might be any parameters traditionally used by input, implicit or frequency SM [3].

Next, we optimize $\boldsymbol{R}_t^{(i)}$ to have it meet the original design specifications. We obtain optimal values of the design parameters $\boldsymbol{x}^{(i+1)}$ as

$$\boldsymbol{x}^{(i+1)} = \arg\min_{\boldsymbol{x}} U\left(\boldsymbol{R}_t^{(i)}(\boldsymbol{x}, \boldsymbol{p}^{(i)})\right). \tag{3}$$

C. Co-simulation-based tuning model

Typically, the tuning model is implemented using the co-calibrated port technology of Sonnet ***em*** [17], allowing us to cut into the structure being optimized and insert tuning components with minimal disturbance of its response [13]. To realize the ETSM algorithm with an arbitrary EM simulator (here, FEKO), we implement $\boldsymbol{R}_t$ as a co-simulation model as explained in Fig. 2 [18]: essential couplings of the optimized structure are evaluated using EM simulation, whereas the designable parameters are modeled by distributed circuit elements (Fig. 2(b)). This allows us to optimize the tuning model with the circuit-theory speed. The tuning model itself is constructed in a circuit simulator (here, Agilent ADS [19]), Fig. 2(c).

D. ETSM algorithm implementation

Figure 3 shows the flowchart of the proposed tuning space mapping algorithm exploiting a co-simulation-based tuning model. The tuning model is initialized before each iteration of the TSM algorithm in order to update the data components containing the *S*-parameters of the EM-simulated sections of the model. The alignment between the tuning and fine models (cf. (2)), as well as the tuning model optimization (3), are computationally cheap because both are performed within a circuit simulator.

Typically, the algorithm is terminated when a satisfactory design is found. Because of the good generalization capability of the co-simulation-based tuning model, two to four iterations usually suffice to conclude the search process.

III. EXAMPLES

In this section, the performance of the co-simulation-based TSM is verified using two examples of microstrip filters. What is more important, we also provide a comprehensive numerical comparison between this technique and several other approaches, including: (i) space mapping (SM) [6], (ii) a gradient-based optimizer (here, Matlab's *fminimax* [21]), and (iii) a derivative-free optimizer (here, a pattern search algorithm [22]).

Space mapping is a recognized surrogate-based optimization methodology that exploits a physically-based coarse model $\boldsymbol{R}_c$ to create a surrogate that is subsequently used in the iterative optimization process similar to (3). Here, the SM surrogate is created using input and frequency SM [6], so that the surrogate is of the form $\boldsymbol{R}_s(\boldsymbol{x}) = \boldsymbol{R}_{c.f}(\boldsymbol{x} + \boldsymbol{c})$, where $\boldsymbol{c}$ is a vector determined to minimize $\|\boldsymbol{R}_f(\boldsymbol{x}^{(i)}) - \boldsymbol{R}_{c.f}(\boldsymbol{x}^{(i)} + \boldsymbol{c})\|$ ($\boldsymbol{x}^{(i)}$ being the current design). Furthermore, $\boldsymbol{R}_{c.f}$ is a frequency-mapped coarse model, i.e., the coarse model 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 $[f_1\ f_2]^T$ also obtained to minimize the misalignment between the coarse and the fine model.

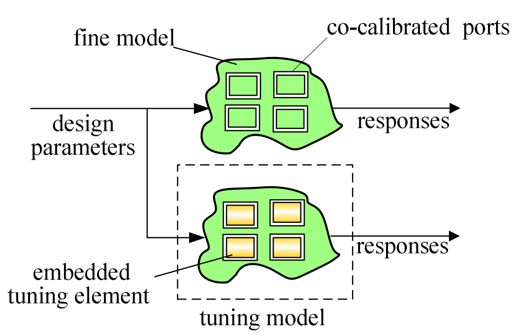

Fig. 1. Conceptual illustration of the tuning model with embedded surrogate elements [10].

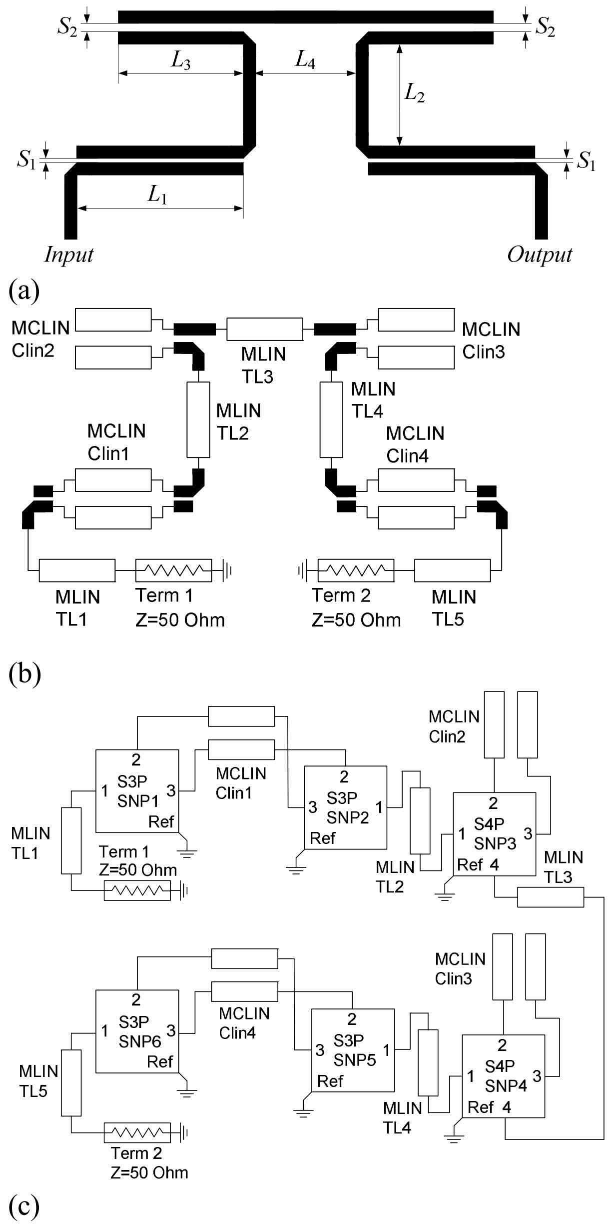

Fig. 2. Co-simulation-based tuning model [18]: (a) a coupled-line bandpass microstrip filter structure [20], (b) its co-simulation tuning model with black sections simulated using an EM solver (here, FEKO) connecting designable tuning components, (c) ADS implementation of the tuning model $\boldsymbol{R}_t$: *S*-parameters of the EM-simulated sections are stored in S3P and S4P data components SNP1 to SNP6. Note that all the designable parameters (microstrip lengths, widths and coupled-line gaps) are associated with the distributed circuit components, which allows fast optimization of the tuning model. On the other hand, simulating parts of the filter

using the EM solver allows us to maintain good accuracy and predictability of the tuning model.

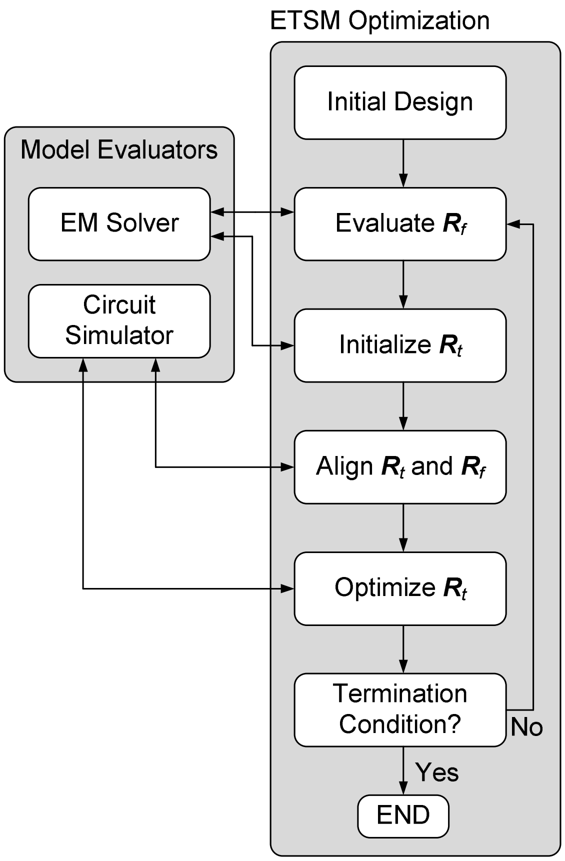

Fig. 3. A flow diagram of the proposed tuning space mapping algorithm exploiting a co-simulation-based tuning model. In each iteration, the tuning model is initialized by updating its data components (obtained by EM-simulation). Both the alignment procedure (2) and the tuning model optimization (3) are performed using a circuit simulator.

Matlab's *fminimax* is a gradient-based routine that uses a sequential quadratic programming (SQP) method [23] to solve the original minimax problem reformulated into an equivalent nonlinear programming problem [21].

The pattern search algorithm [22] is a derivative-free search routine that examines the neighborhood of the current design on a predefined grid and refines the grid in case this local search fails to improve the design. A few other mechanisms, such as a line search along promising directions, are also involved.

A. Coupled-line microstrip bandpass filter [20]

Consider the coupled-line bandpass filter [20] shown in Fig. 2(a). The design parameters are $\boldsymbol{x} = [L_1\ L_2\ L_3\ L_4\ S_1\ S_2]^T$ mm. The fine model $\boldsymbol{R}_f$ is simulated in FEKO [16]. The design specifications are $|S_{21}| \geq -3$ dB for 2.3 GHz $\leq \omega \leq$ 2.5 GHz, and $|S_{21}| \leq -20$ dB for 1.5 GHz $\leq \omega \leq$ 2.2 GHz, and 2.6 GHz $\leq \omega \leq$ 3.3 GHz. The initial design is $\boldsymbol{x}^{(0)} = [29.0\ 5.0\ 8.0\ 24.0\ 0.1\ 0.1]^T$ mm (specification error +31 dB).

A schematic of the co-simulation-based tuning model is shown in Fig. 2(b). Sub-sections marked black are simulated in FEKO. Due to symmetry, only two sub-sections need independent evaluation. The tuning model is handled by Agilent ADS [19] (Fig. 2(c)). The alignment procedure (2) uses the vector $\boldsymbol{p}$ consisting of dielectric constants (initial value 3.0) as well as substrate heights (initial value 0.51 mm) of the distributed circuit components corresponding to the design variables L_1 to L_4.

Figure 4 shows the fine model response at the initial design as well as the response of the tuning model at $\boldsymbol{x}^{(0)}$ before and after alignment. Figure 5 shows the fine model response after the first iteration of the ETSM algorithm, which is already very good, satisfying the design specifications (specification error –1.3 dB). Figure 6 shows the fine model response at the final design obtained in two iterations, $\boldsymbol{x}^{(2)} = [25.38\ 5.32\ 8.50\ 20.35\ 0.085\ 0.1]^T$ mm (specification error –1.5 dB).

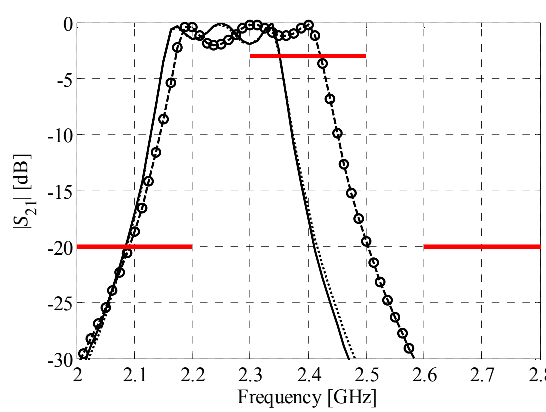

Fig. 4. Coupled-line bandpass filter: responses at the initial design $\boldsymbol{x}^{(0)}$: the fine model (solid line), the tuning model (dashed line with circles), and the aligned tuning model (dotted line).

For comparison, the filter was also optimized using Matlab's *fminimax* routine [21], a pattern search algorithm [22], as well as a space mapping algorithm exploiting input, frequency and output SM [6] (the coarse model utilized by SM is shown in Fig. 7). The results are shown in Table 1.

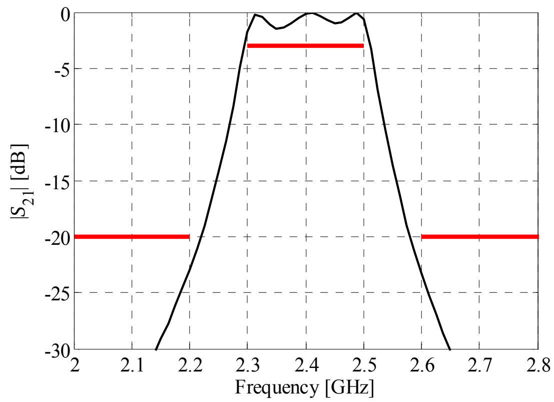

Fig. 5. Coupled-line bandpass filter: fine model response after one ETSM iteration.

It can be observed that both space mapping and gradient-based search fail to find a design satisfying the specifications. The design obtained using pattern search is slightly better than that obtained by the technique described here; however, the design cost is substantially higher.

B. Wideband bandstop microstrip filter [23]

Consider the wideband bandstop microstrip filter [23] in Fig. 8(a). The design parameters are $\boldsymbol{x} = [L_r\ W_r\ L_c\ W_c\ G_c]^T$. The fine model $\boldsymbol{R}_f$ is simulated in FEKO [16]. The design specifications are $|S_{21}| \geq -3$ dB for 1.0 GHz $\leq \omega \leq$ 2.0 GHz, $|S_{21}| \leq -20$ dB for 3.0 GHz $\leq \omega \leq$ 9.0 GHz, and $|S_{21}| \geq -3$ dB for 10.0 GHz $\leq \omega \leq$ 11.0 GHz. The initial design is $\boldsymbol{x}^{(0)} = [7.0\ \ 1.0\ \ 9.0\ \ 0.2\ \ 0.1]^T$ mm (specification error +16 dB).

A schematic of the tuning model is shown in Fig. 8(b). The tuning model is implemented in Agilent ADS [19] (Fig. 8(c)).

The alignment procedure (2) uses the vector $\boldsymbol{p}$ consisting of dielectric constants (initial value 3.38) as well as the substrate heights (initial value 0.508 mm) of the distributed circuit components corresponding to design variables L_r and L_c.
Figure 9 shows the fine model response at the initial design as well as the response of the tuning model at $\boldsymbol{x}^{(0)}$ before and after alignment. Figures 10 and 11 show the fine model response after the first iteration of the ETSM algorithm, and at the final design obtained in four iterations, $\boldsymbol{x}^{(4)} = [7.375\ \ 1.265\ \ 7.958\ \ 0.051\ \ 0.120]^T$ mm (specification error –2.1 dB). The design obtained in one iteration of the ETSM algorithm is close to satisfying the design specifications, which demonstrates the robustness of our proposed approach.

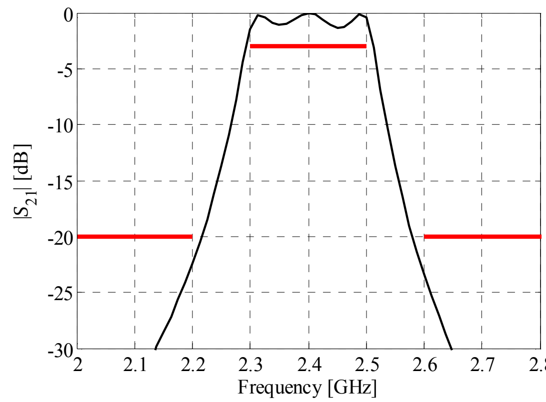

Fig. 6. Coupled-line bandpass filter: fine model response at the final design obtained in two ETSM iterations.

Table 1: Coupled-line bandstop filter: co-simulation-based tuning versus other optimization approaches: design quality and computational cost comparison

Algorithm	Best design found*	Design cost#
Co-simulation-based tuning	–1.3 dB	3
Space mapping	+1.5 dB	8
Matlab (*fminimax*)	+22 dB	208
Pattern search	–1.7 dB	155

* Specification error at the final (optimized design).
\# Number of the fine model evaluations.

As before, the filter was also optimized using Matlab's *fminimax* routine [21], a pattern search algorithm [22], as well as a space mapping algorithm exploiting input, frequency and output SM [6]. Figure 12 shows the coarse model used by the SM algorithm. The results (Table 2), indicate that our technique outperforms the other methods. Although space mapping finds a design that is only slightly worse, the computational cost is twice as high. Direct optimization is far more expensive: only *fminimax* is able to find a design satisfying the specifications.

C. Discussion

The results of our performance comparison between the co-simulation-based TSM and other techniques are quite consistent for both our examples. It can be observed that the space mapping algorithm does not perform as well as TSM, which is an indication that the TSM tuning model has better generalization capability (because part of the tuning model comes from EM simulation). It is known [25] that SM can perform better for a carefully selected surrogate model, however, such selection requires user experience as well as some computational effort [25].

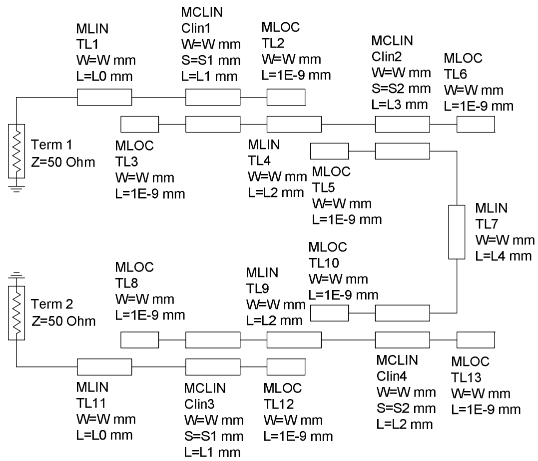

Fig. 7. Coupled-line bandpass filter: the coarse model utilized by the space mapping algorithm.

Both the gradient-based algorithm and pattern search are computationally far more expensive than TSM and are not as reliable. An issue that has to be taken into account while using an algorithm such as *fminimax* is the numerical noise that is always present in EM-simulation-based objective functions. In particular, a minimum step for finite differentiation has to be carefully selected (typically, a few orders of magnitude larger than the default value of 10^{-8}), otherwise, the algorithm may fail or even get stuck at the initial design. Similar issues have to be addressed for a pattern search algorithm, e.g., the results are typically sensitive to the size of the initial grid.

These remarks indicate that while all optimization methods require certain tuning and are sensitive to their control parameters, it seems that the co-simulation TSM approach is more reliable in this respect. This is reflected not only by the quality of the designs produced by TSM but also by the low computational cost of the optimization process.

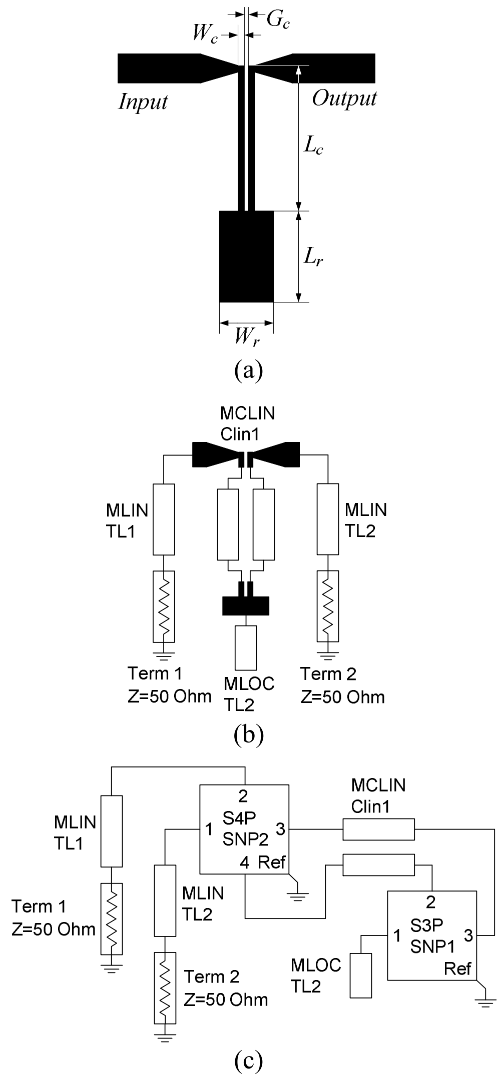

Fig. 8. Wideband bandstop filter: (a) geometry [23], (b) conceptual diagram of the co-simulation-based tuning model, (c) tuning model (Agilent ADS).

IV. CONCLUSION

We present an implementation of the ETSM algorithm that exploits a co-simulation-based tuning model of the microwave structure under consideration. In our proposed approach, critical fine-model couplings are simulated using an EM solver, whereas the designable parameters are modeled by distributed circuit elements. This facilitates good predictability by the tuning model, and, at the same time, design optimization with circuit-theory speed. More importantly, our ETSM algorithm can be implemented using any electromagnetic simulator. We demonstrate that our approach yields a satisfactory design for the modest computational cost of just a few electromagnetic simulations.

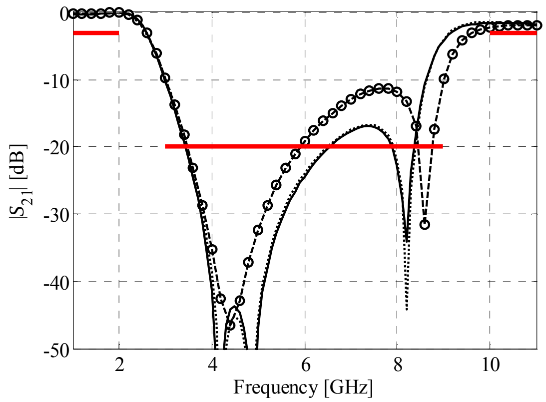

Fig. 9. Wideband bandstop filter: responses at the initial design $\boldsymbol{x}^{(0)}$: the fine model (solid line), the tuning model (dashed line with circles), and the aligned tuning model (dotted line).

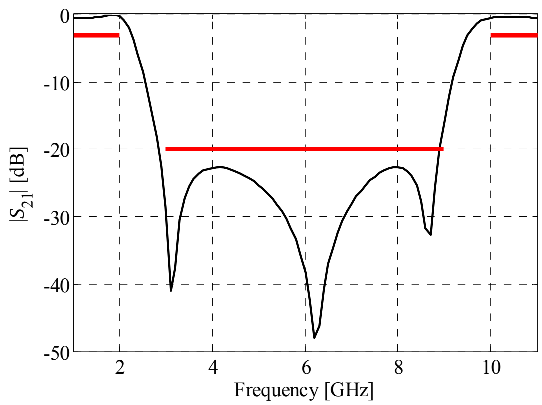

Fig. 10. Wideband bandstop filter: fine model response after one ETSM iteration. The design specifications are satisfied except for a small frequency shift in the stop band.

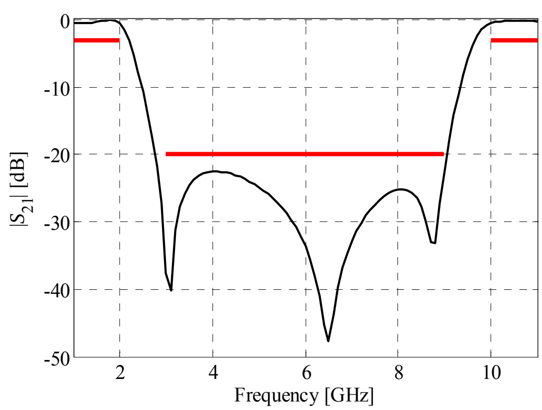

Fig. 11. Wideband bandstop filter: fine model response at the final design obtained in four ETSM iterations.

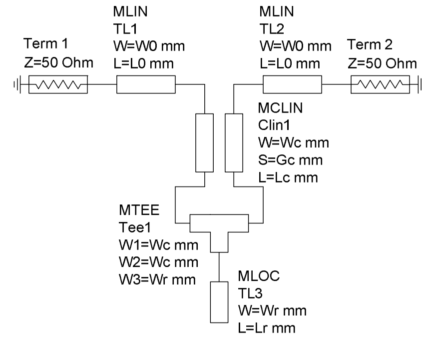

Fig. 12. Wideband bandstop filter: the coarse model used by the space mapping algorithm.

Table 2: Wideband bandstop filter: co-simulation-based tuning versus other optimization approaches: design quality and computational cost comparison

Algorithm	Best design found*	Design cost#
Co-simulation-based tuning	–2.1 dB	5
Space mapping	–1.5 dB	10
Matlab (*fminimax*)	–0.6 dB	151
Pattern search	+0.2 dB	203

* Specification error at the final (optimized design).
\# Number of the fine model evaluations.

ACKNOWLEDGEMENT

The authors thank Agilent Technologies, Santa Rosa, CA, for making ADS available. This work was supported in part by the Reykjavik University Development Fund under Grant T10006, by the Icelandic Centre for Research (RANNIS) Grant 110034021, and by the Natural Sciences and Engineering Research Council of Canada under Grants RGPIN7239-06 and STPGP381153-09.

REFERENCES

[1] N. V. Queipo, R. T. Haftka, W. Shyy, T. Goel, R. Vaidynathan, and P. K. Tucker, “Surrogate-Based Analysis and Optimization,” *Progress in Aerospace Sciences*, vol. 41, no. 1, pp. 1-28, Jan. 2005.

[2] A. I. J. Forrester and A. J. Keane, “Recent Advances in Surrogate-Based Optimization,” *Prog. in Aerospace Sciences*, vol. 45, no. 1-3, pp. 50-79, Jan.-April, 2009.

[3] J. W. Bandler, Q. S. Cheng, S. A. Dakroury, A. S. Mohamed, M. H. Bakr, K. Madsen, and J. Søndergaard, “Space Mapping: The State of the Art,” *IEEE Trans. Microwave Theory Tech.*, vol. 52, no. 1, pp. 337-361, Jan. 2004.

[4] D. Echeverria and P. W. Hemker, “Space Mapping and Defect Correction,” *CMAM The International Mathematical Journal Computational Methods in Applied Mathematics,* vol. 5, no. 2, pp. 107-136, 2005.

[5] S. Amari, C. LeDrew, and W. Menzel, “Space-Mapping Optimization of Planar Coupled-Resonator Microwave Filters,” *IEEE Trans. Microwave Theory Tech.*, vol. 54, no. 5, pp. 2153-2159, May 2006.

[6] S. Koziel, J.W. Bandler, and K. Madsen, “A Space Mapping Framework for Engineering Optimization: Theory and Implementation,” *IEEE Trans. Microwave Theory Tech*., vol. 54, no. 10, pp. 3721-3730, Oct. 2006.

[7] G. Crevecoeur, L. Dupre, and R. Van de Walle, “Space Mapping Optimization of the Magnetic Circuit of Electrical Machines Including Local Material Degradation,” *IEEE Trans. Magn.*, vol. 43, no 6, pp. 2609-2611, June 2007.

[8] S. Koziel, Q. S. Cheng, and J. W. Bandler, “Space Mapping,” *IEEE Microwave Magazine*, vol. 9, no. 6, pp. 105-122, Dec. 2008.

[9] S. Koziel, J. Meng, J. W. Bandler, M. H. Bakr, and Q. S. Cheng, “Accelerated Microwave Design Optimization with Tuning Space Mapping,” *IEEE Trans. Microwave Theory and Tech.*, vol. 57, no. 2, pp. 383-394, Feb. 2009.

[10] Q. S. Cheng, J. W. Bandler, and S. Koziel, “Tuning Space Mapping Optimization Exploiting Embedded Surrogate Elements,” *IEEE MTT-S Int. Microwave Symp. Dig*, Boston, MA, pp. 1257-1260, 2009.

[11] D. Swanson and G. Macchiarella, “Microwave Filter Design by Synthesis and Optimization,” *IEEE Microwave Magazine*, vol. 8, no. 2, pp. 55-69, Apr. 2007.

[12] J. C. Rautio, “EM-Component-Based Design of Planar Circuits,” *IEEE Microwave Magazine*, vol. 8, no. 4, pp. 79-90, Aug. 2007.

[13] J. C. Rautio, “Perfectly Calibrated Internal Ports in EM Analysis of Planar Circuits,” *IEEE MTT-S Int. Microwave Symp. Dig.*, Atlanta, GA, pp. 1373-1376, June 2008.

[14] S. Shin and S. Kanamaluru, “Diplexer Design using EM and Circuit Simulation Techniques,” *IEEE Microwave Magazine*, vol. 8, no. 2, pp.77-82, Apr. 2007.

[15] A. Bhargava, “Designing Circuits using an EM/Circuit Co-Simulation Technique,” *RF Design*, p. 76, Jan. 2005.

[16] FEKO, Suite 5.5, EM Software & Systems-S.A. (Pty) Ltd, 32 Techno Lane, Technopark, Stellenbosch, 7600, South Africa, 2009.

[17] ***em***™ Version 12.54, Sonnet Software, Inc., 100 Elwood Davis Road, North Syracuse, NY 13212, USA, 2010.

[18] S. Koziel and J. W. Bandler, “Co-Simulation Based Tuning Space Mapping with FEKO for Computationally Efficient Optimization of Microwave Structures,” *Int. Review of Progress in Applied Comp. Electromagnetics*, Tampere, Finland, pp. 41-46, 2010.

[19] Agilent ADS, Version 2008, Agilent Technologies, 1400 Fountaingrove Parkway, Santa Rosa, CA 95403-1799, 2008.

[20] H. M. Lee and C. M. Tsai, “Improved Coupled-Microstrip Filter Design using Effective Even-Mode and Odd-Model Characteristic Impedances,” *IEEE Trans. Microwave Theory Tech.*, vol. 53, no. 9, pp. 2812-2818, Sept. 2005.

[21] Matlab™, Version 7.6, The MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760-2098, 2008.

[22] T. G. Kolda, R. M. Lewis, and V. Torczon, “Optimization by Direct Search: New Perspectives on Some Classical and Modern Methods,” *SIAM Review*, vol. 45, no. 3, pp. 385-482, 2003.

[23] R. K. Brayton, S. W. Director, G. D. Hachtel, and L. Vidigal, “A New Algorithm for Statistical Circuit Design Based on Quasi-Newton Methods and Function Splitting,” *IEEE Trans. Circuit and Systems*, vol. CAS-26, pp. 784-794, Sept. 1979.

[24] M. Y. Hsieh and S. M. Wang, “Compact and Wideband Microstrip Bandstop Filter,” *IEEE Microwave and Wireless Component Letters*, vol. 15, no. 7, pp. 472-474, July 2005.

[25] S. Koziel, J. W. Bandler, and K. Madsen, “Quality Assessment of Coarse Models and Surrogates for Space Mapping Optimization,” *Optimization and Engineering*, vol. 9, no. 4, pp. 375-391, 2008.

Slawomir Koziel received the M.Sc. and Ph.D. degrees in Electronic Engineering from Gdansk University of Technology, Poland, in 1995 and 2000, respectively. He also received the M.Sc. degrees in Theoretical Physics and in Mathematics, in 2000 and 2002, respectively, as well as the Ph.D. in Mathematics in 2003, from the University of Gdansk, Poland. He is currently an Associate Professor with the School of Science and Engineering, Reykjavik University, Iceland. His research interests include CAD and modeling of microwave circuits, surrogate-based optimization, space mapping, circuit theory, analog signal processing, evolutionary computation and numerical analysis.

John W. Bandler studied at Imperial College, London, England, and received the B.Sc.(Eng.), Ph.D., and D.Sc.(Eng.) degrees from the University of London, England, in 1963, 1967, and 1976, respectively. He joined McMaster University, Canada, in 1969. He is now Professor Emeritus. He was President of Optimization Systems Associates Inc., which he founded in 1983, until November 20, 1997, the date of acquisition by Hewlett-Packard Company. He is President of Bandler Corporation, which he founded in 1997. He is a Fellow of several societies, including the IEEE, the Canadian Academy of Engineering, and the Royal Society of Canada. In 2004, he received the IEEE MTT-S Microwave Application Award.