Micronet R & D Innovations

2001–2002

1. Number and Title of Project: *C.6.CAR2: Design Optimization Methodology for High-Speed/High Frequency Circuits and Systems*

2. Title of Overview: *Space Mapping Optimization Exploiting Adjoint Sensitivities*

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4. Innovation Overview:

The Space Mapping (SM) approach involves a suitable calibration of a fine model by a physically-based "coarse" surrogate. The fine model may be time intensive and field theoretic and accurate, while the surrogate is a faster (less accurate) representation.

We present, for the first time, new techniques for exploiting exact sensitivities in EM-based circuit design in the context of SM technology. If the EM simulator is capable of providing gradient information, these gradients can be exploited to enhance a coarse surrogate. New approaches for utilizing derivatives in the Parameter Extraction (PE) process and mapping update are presented.

We present the Gradient Parameter Extraction (GPE) algorithm. In GPE we match not only the responses of the fine and the coarse models but also the corresponding Jacobians.

If we have exact derivatives throughout, we can use them to obtain the mapping at each iteration. If we do not have exact derivatives, various approaches to initializing or constraining the mapping can be devised, for example, we can use finite differences. Either matrix may be updated using a Broyden update. Hybrid schemes can be formally developed following the integrated gradient approximation approach to optimization by Bandler *et. al*.

Space Mapping Optimization Exploiting Adjoint Sensitivities

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Introduction

The SM approach involves a suitable calibration of a fine model by a physically-based "coarse" surrogate. The fine model may be time intensive and field theoretic and accurate, while the surrogate is a faster (less accurate) representation.

We present, for the first time, new techniques for exploiting exact sensitivities in EM-based circuit design in the context of SM technology. If the EM simulator is capable of providing gradient information, these gradients can be exploited to enhance a coarse surrogate. New approaches for utilizing derivatives in the parameter extraction process and mapping update are presented.

Gradient Parameter Extraction (GPE)

At the *j*th iteration we obtain $\boldsymbol{x}_c^{(j)}$ through a Gradient Parameter Extraction (GPE) process:

$$\boldsymbol{x}_c^{(j)} = \arg\min_{\boldsymbol{x}_c} \left\| [\boldsymbol{e}_0^T \quad \lambda\boldsymbol{e}_1^T \quad \cdots \quad \lambda\boldsymbol{e}_n^T]^T \right\|, \ \lambda \geq 0 \tag{1}$$

where λ is a weighting factor and $\boldsymbol{E} = [\boldsymbol{e}_1 \ \boldsymbol{e}_2 \ \ldots \ \boldsymbol{e}_n]$.

$$\begin{aligned} \boldsymbol{e}_0 &= \boldsymbol{R}_f(\boldsymbol{x}_f^{(j)}) - \boldsymbol{R}_c(\boldsymbol{x}_c) \\ \boldsymbol{E} &= \boldsymbol{J}_f(\boldsymbol{x}_f^{(j)}) - \boldsymbol{J}_c(\boldsymbol{x}_c)\boldsymbol{B} \end{aligned} \tag{2}$$

where $\boldsymbol{J}_f$ and $\boldsymbol{J}_c$ are the fine and coarse Jacobians at $\boldsymbol{x}_f$ and $\boldsymbol{x}_c$, respectively ($\boldsymbol{J}_f, \boldsymbol{J}_c \in \Re^{M \times n}$; $M \geq n$).

Mapping Update Alternatives

If we have exact derivatives throughout, we can use them to obtain $\boldsymbol{B}$ at each iteration in the Parameter Extraction (PE). Note that this matrix can be iteratively fed back into the GPE process and refined before making a step in the fine model space.

If we do not have exact derivatives, various approaches to initializing or constraining $\boldsymbol{B}$ can be devised, for example, we can use finite differences. Either matrix may be updated using a Broyden update. Hybrid schemes can be formally developed following the integrated gradient approximation approach to optimization by Bandler *et al.* [1].

On the assumption that the fine and coarse models share the same physical background, Bakr *et al.* [2] suggested that $\boldsymbol{B}$ could be better conditioned, in the PE process, if it is constrained to be close to the identity matrix $\boldsymbol{I}$.

Bandstop Microstrip Filter with Open Stubs [3]

Our approach is applied to a symmetrical bandstop microstrip filter with open stubs. An alumina substrate with thickness H = 25 mil, width W_0 = 25 mil and dielectric constant ε_r = 9.4 is used for a 50 Ω feeding line. The coarse and fine models are shown in Figs. 1 and 2, respectively. The design parameters are $\boldsymbol{x}_f = [W_1 \ W_2 \ L_0 \ L_1 \ L_2]^T$. The design specifications are

$$\begin{aligned} |S_{21}| &\leq 0.05 \quad \text{for } 9.3\,\text{GHz} \leq \omega \leq 10.7\,\text{GHz} \text{ and,} \\ |S_{21}| &\geq 0.9 \quad \text{for } 12\,\text{GHz} \leq \omega \text{ and } \omega \leq 8\,\text{GHz} \end{aligned}$$

Sonnet's ***em***™ [4] driven by Empipe™ [5] is employed as the fine model, using a high-resolution grid with a 1mil×1mil cell size. We use OSA90/hope™ [5] built-in transmission line elements and classical formulas to represent the coarse model. $\boldsymbol{x}_c^* = [4.560 \ 9.351 \ 107.80 \ 111.03 \ 108.75]^T$ (in mils). We use 21 points per frequency sweep. We utilize the real and imaginary parts of S_{11} and S_{21} in the PE. Finite differences estimate the fine and coarse Jacobians. A hybrid approach is used to update $\boldsymbol{B}$. The algorithm converges in 5 iterations. The initial and final responses are shown in Figs. 3 and 4, respectively. The reduction of $\|\boldsymbol{x}_c - \boldsymbol{x}_c^*\|_\infty$ versus iterations is shown in Fig. 5.

Conclusions

We present a family of techniques for exploiting exact sensitivities in SM optimization. Available gradients can initialize mapping approximations. Exact or approximate Jacobians of responses can be utilized. For flexibility, we propose different possible "mapping matrices" for the PE processes and SM iterations. Broyden updates can be used. Final mappings are useful in statistical analysis and yield optimization.

Acknowledgement

The authors thank Dr. J.C. Rautio, President, Sonnet Software, Inc., Liverpool, NY, for making ***em***™ available.

References

[1] J.W. Bandler, S.H. Chen, S. Daijavad and K. Madsen, "Efficient optimization with integrated gradient approximations," *IEEE Trans. Microwave Theory Tech.,* vol. 36, 1988, pp. 444-455.

[2] M.H. Bakr, J.W. Bandler, K. Madsen and J. Søndergaard, "Review of the space mapping approach to engineering optimization and modeling," *Optimization and Engineering*, vol. 1, 2000, pp. 241-276.

[3] M.H. Bakr, J.W. Bandler, M.A. Ismail, J.E. Rayas-Sánchez and Q.J. Zhang, "Neural space-mapping optimization for EM-based design," *IEEE Trans. Microwave Theory Tech.*, vol. 48, 2000, pp. 2307-2315.

[4] ***em***™ Version 5.1a, Sonnet Software, Inc., 1020 Seventh North Street, Suite 210, Liverpool, NY 13088, 1997.

[5] OSA90/hope™ and Empipe™ Version 4.0, formerly Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7, 1997, now Agilent EEsof EDA, 1400 Fountaingrove Parkway, Santa Rosa, CA 95403-1799.

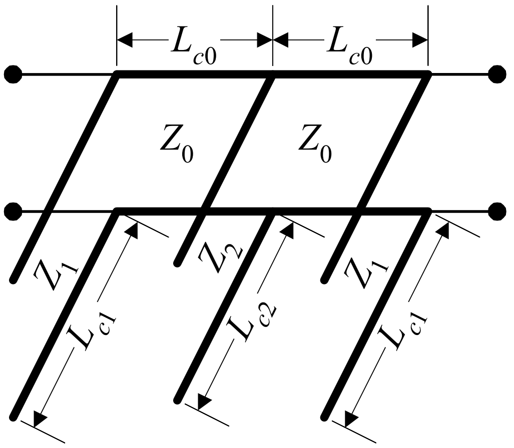

Fig. 1. Bandstop microstrip filter with open stubs: coarse model.

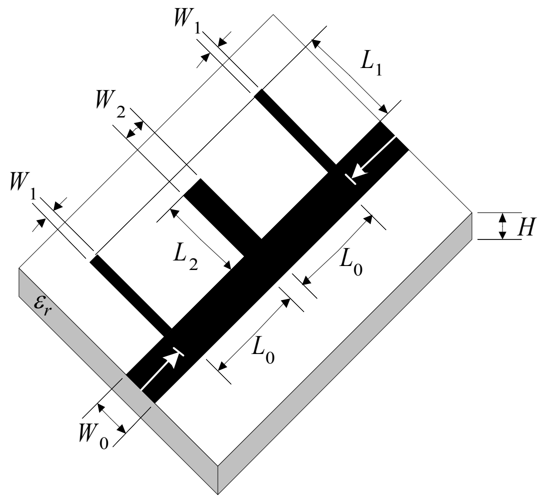

Fig. 2. Bandstop microstrip filter with open stubs: fine model.

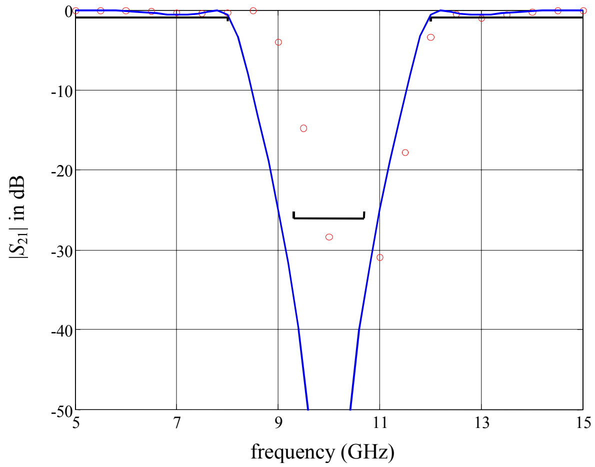

Fig. 3. Optimal OSA90/hope target coarse response (—) and corresponding ***em*** fine model response at the starting point (o) for the bandstop microstrip filter.

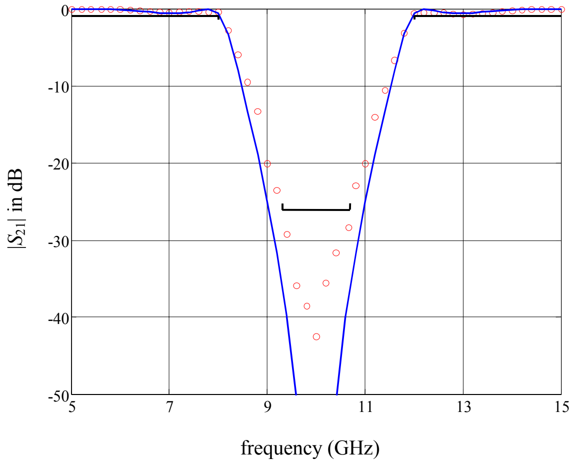

Fig. 4. Optimal OSA90/hope target coarse response (—) and ***em*** fine model response at the final design (o) for the bandstop microstrip filter.

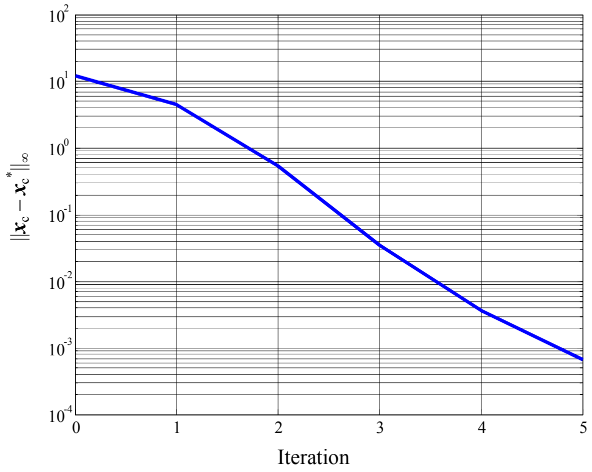

Fig. 5. Reduction of $\|\boldsymbol{x}_c - \boldsymbol{x}_c^*\|_\infty$ versus iterations.